# Development of a Pulmonary Simulator Utilizing Windkessel Modeling Techniques for Simulating Various Patient Populations within a Mock Circulatory System

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## Introduction

An adaptive pulmonary simulator (PS) is essential for analyzing the possible impact of external factors on the performance, safety, and reliability of a left ventricular assist device (LVAD) within a mock circulatory system (MCS). In order to accurately and precisely reproduce the conditions within the pulmonary system, a PS should not only account for the ability of the pulmonary system to supply blood flow at specific pressures, but likewise consider the dynamics of systemic outflow. This would provide an accurate pressure and flow rate return feed back into the left ventricular portion of the MCS (i.e. the

## Methods and Materials

- A mock circulatory system (MCS) simulates the temporal aspects of the human circulatory system in a bench-top hydraulic circuit that accurately and precisely replicates time-dependent cardiovascular conditions.
- A pulmonary simulator reproduces left atrial pressure as a function of time. The simulator allows for an accurate pressure and flow rate return feed back into the left ventricular portion of the MCS, i.e. the initial conditions of the left heart.
- This temporal model is capable of generating the left atrial pressure (LAP) waveform for given pulmonary factors, systemic variables, and aortic conditions. **Figure 1** reveals the process flow diagram.
- Using MathWorks' Simulink® Simscape™, a computational temporal model, **Figure 2,** was developed embedding Windkessel modeling techniques and a cardiovascular system model developed by J. F. de Canete, et al. [1].
- The Windkessel effect accounts for the shape of the arterial blood pressure waveform in terms of the interaction between the compliance of the aorta and large elastic arteries (Windkessel vessels) [2, 3].
  - Every element of an RCL electrical circuit can be related to its analogous anatomical counterpart within the circulatory system, i.e. arterial compliance is analogous to a capacitor, blood inertia to an inductor, and periph-

| | | Pediatric | Adult | Geriatric |
|---|---|---|---|---|
| Clinical | LAP [mmHg] | 10-12 [4] | 2-12 [5] | 5-15 [6] |
| | Cardiac Output [L/min] | 1-3 [4] | 4-8 [5] | 3-6 [6] |
| | AoP [mmHg] | 70-75 [4] | 70-105 [5] | 75-115 [7] |
| Windkessel Circuit Variables | Initial Voltage [V] | 10.75 | 7 | 10 |
| | Venous Pulmonary Compliance [F] | 26.39 | 5.84 | 5.31 |
| | Pulmonary Resistance [Ohm] | 0.152 | 0.203 | 0.187 |

(e)

## Results

This system is responsive to temporal changes in hemodynamic conditions and can produce a range of LAP waveforms for simulating difference patient populations as shown in **Figure 3 and 4**.

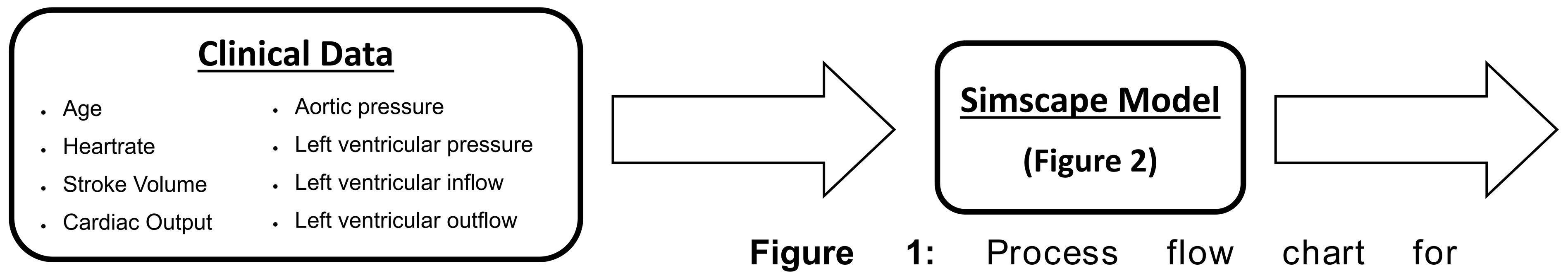


**Figure 1:** Process flow chart for development of robust analysis of clinical data for simulating specific patient populations

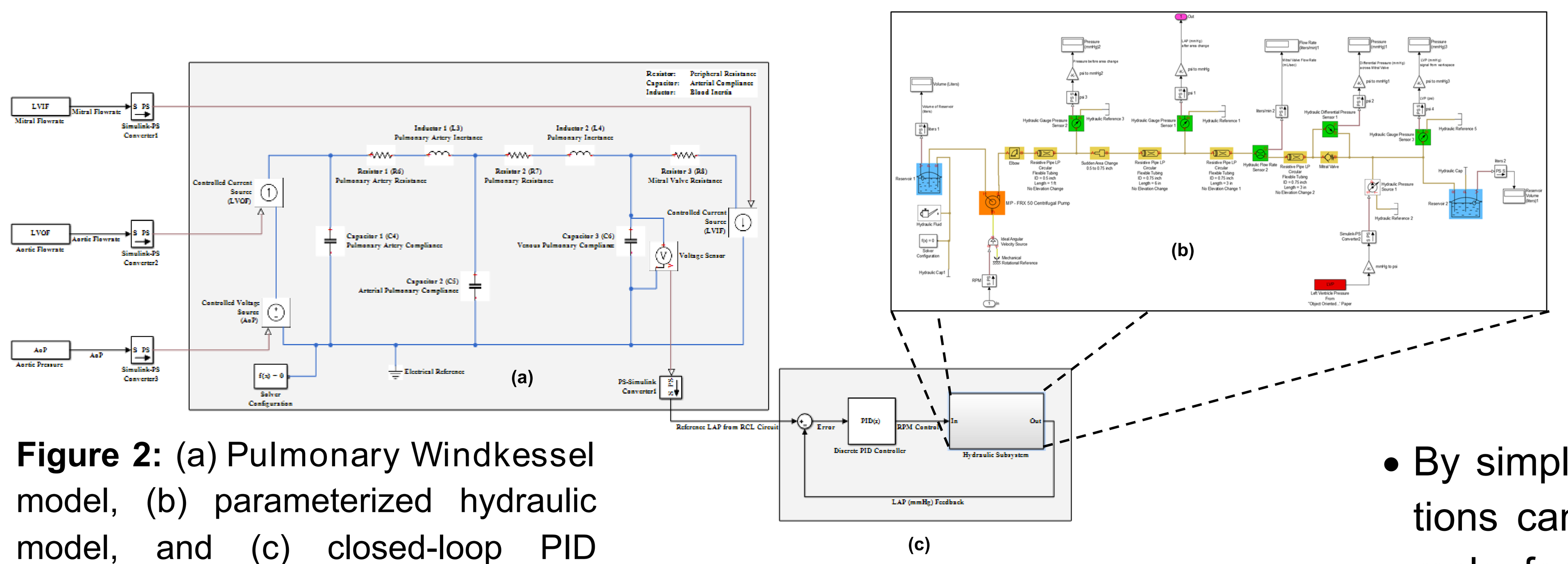


**Figure 2:** (a) Pulmonary Windkessel model, (b) parameterized hydraulic model, and (c) closed-loop PID controller setup developed on MathWorks' Matlab® and Simulink®

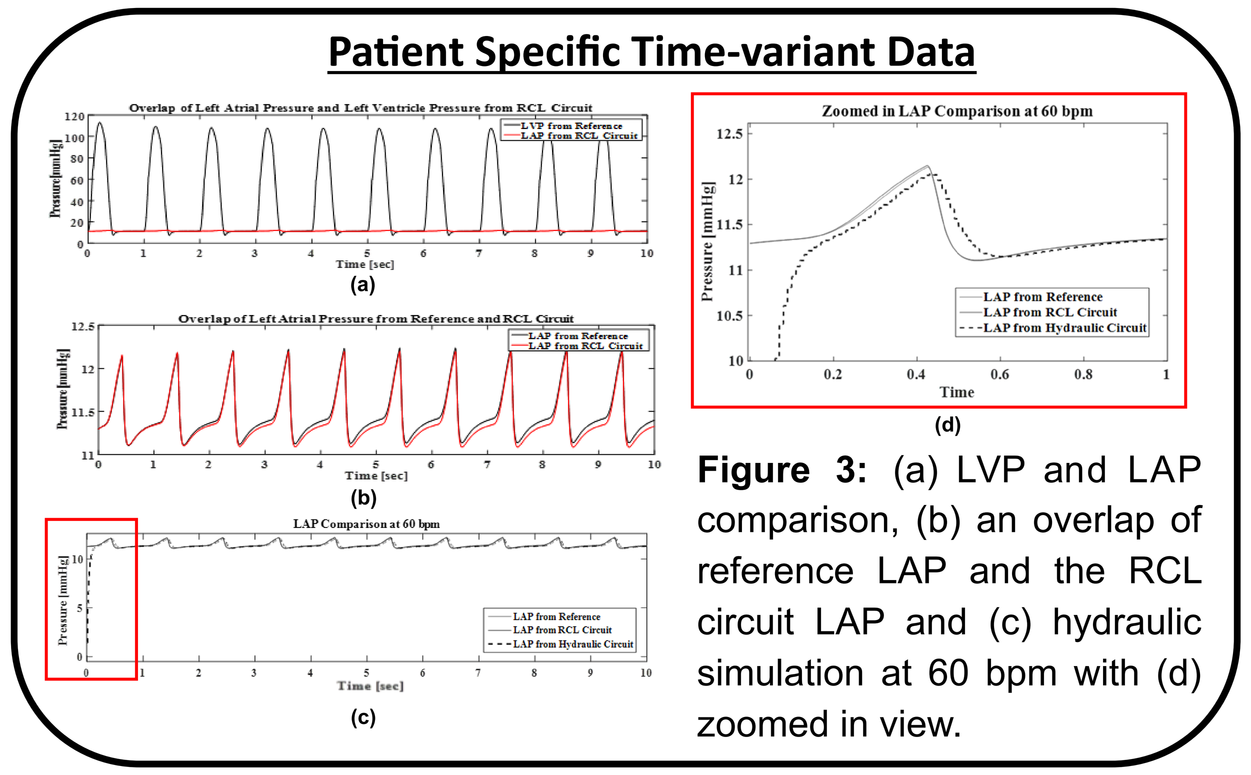


**Figure 3:** (a) LVP and LAP comparison, (b) an overlap of reference LAP and the RCL circuit LAP and (c) hydraulic simulation at 60 bpm with (d) zoomed in view.

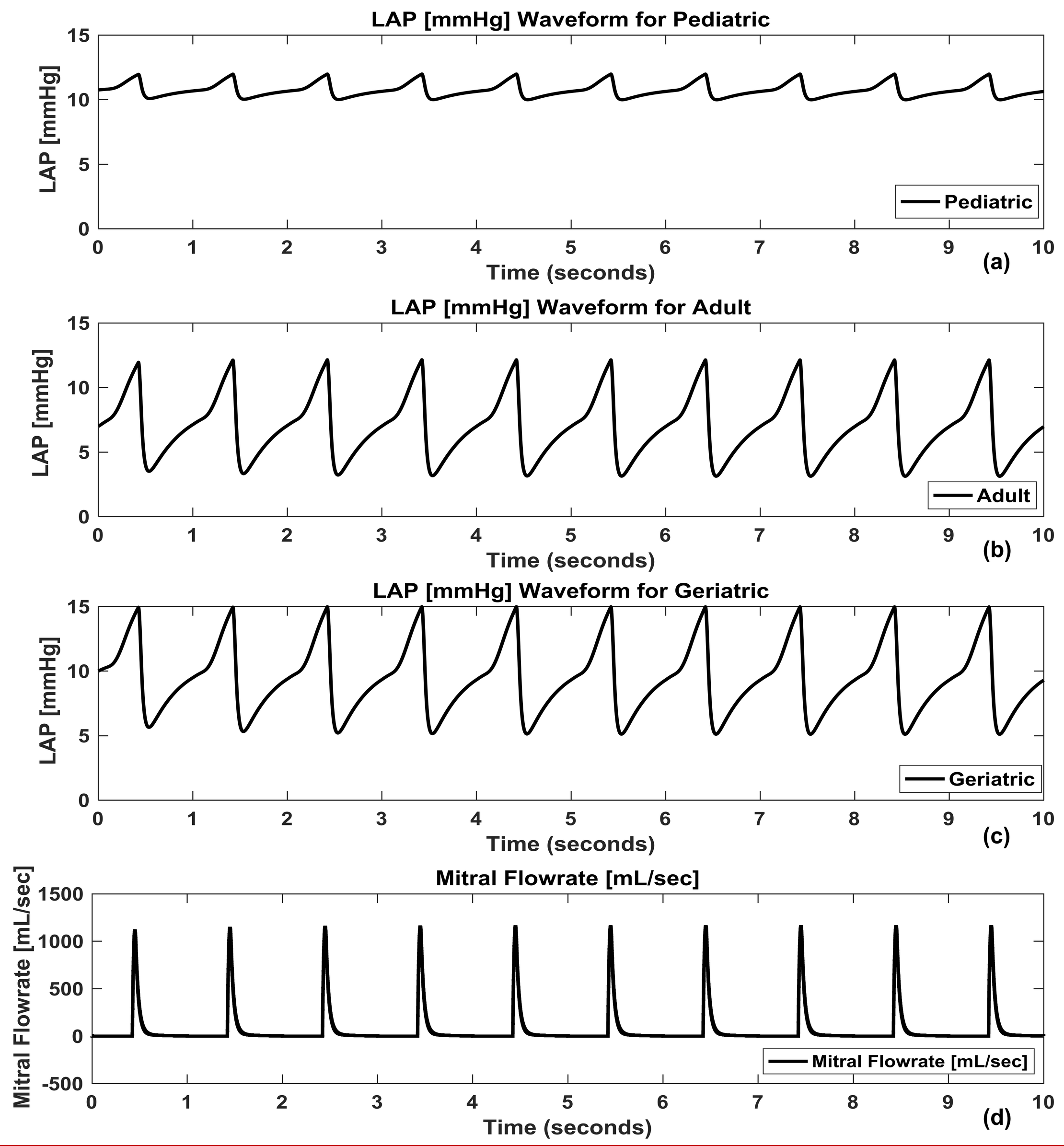


**Figure 4:** LAP of (a) pediatric, (b) adult, (c) geriatric, and (d) mitral flow rate produced by the Windkessel model based on the clinical data presented in (e)

## Conclusions

- The adaptability of this model allows for the reproduction of a broad range of circulatory conditions (i.e. different patient populations) without the limitations of a dedicated hardware platform.
- By simply adjusting the RCL values, LAP for different patient populations can be replicated with the MCS, e.g. pediatric, adult, geriatric, male, female, etc.
- The use of an embedded Windkessel section illustrates the adaptability of this approach to include a variety of circulatory model formats in the place of the chosen section.
- Sparse time-dependent clinical data can be inputted into this system to produce responsive left atrial pressure as a function of time.

## Future Work

- Verification and validation (V&V) studies will be completed utilizing the MCS developed by the Cajun Artificial Heart Laboratory (CAHL).
- This method of analysis can drive computational fluid dynamic (CFD) studies on specific patient populations.

## References

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