# Multi-Scale Modeling of Hypertension

AI Veress[1], GM Raymond[1], GT Gullberg[2], JB Bassingthwaighte[1]

[1]University of Washington, Seattle, WA, USA
[2]E O Lawrence Berkeley National Laboratory, Berkeley, CA, USA

## Abstract

*The focus of this work is the coupling of a 1-D lumped parameter model representing the circulatory system to a 3-D finite element based left ventricle (LV) model in order to study the effects of mild hypertension on the cardiovascular system. A Finite Element LV model under normotensive loading (116/80 mmHg) was developed as well as a mild hypertension (165/90 mmHg) model. In both cases, coupled analysis was utilized so that at one diastolic time point and four systolic time points the values for the LV volumes and pressures were determined from the steady-state JSim solution. The normotensive model had an average first principal stress of 39.1KPa while the hypertensive case showed an increased value of 51.8KPa representing a 32.3% increase. A relatively mild increase in the afterload resulted in a pronounced increase in workload to maintain the same systemic flow.*

## 1. Introduction

Finite element (FE) based computational models of the heart have been developed to study the function of the normal heart as well as to study various pathologies such as ischemia, infarction and heart failure. As sophisticated as these models are, they generally lack an essential prerequisite for correct performance, namely the connection to a model of the circulatory system providing the time-varying impedance. In these cases, pressure boundary conditions were applied a priori, but are not able to simulate changing conditions in the cardiovascular system such as occur with forced exhalation (as with a Valsalva or in playing the trumpet) or with hypertension.

In order to overcome this deficit, a coupled analysis system was developed. A circulatory model running under the JSim analysis package [1] was coupled to a left ventricle (LV) model developed for and analyzed using the finite element package NIKE3d [2] in order to study the effects of mild hypertension on the cardiovascular system.

## 2. Methods

The FE LV model (Fig. 1) was based on the cardiac geometry of a normal 25-year-old male (high resolution CT). The myocardium was represented using realistic material models, parameters and fiber definitions. [3] An active contraction model formulated by Guccione et al. [3, 4] provided the active contractile stress responsible

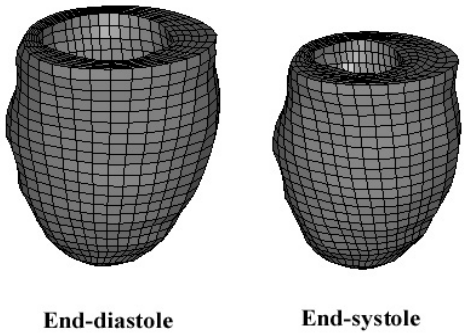


Figure 1. The left ventricle FE model in the end-diastolic (left) and end-systolic (right) configurations.

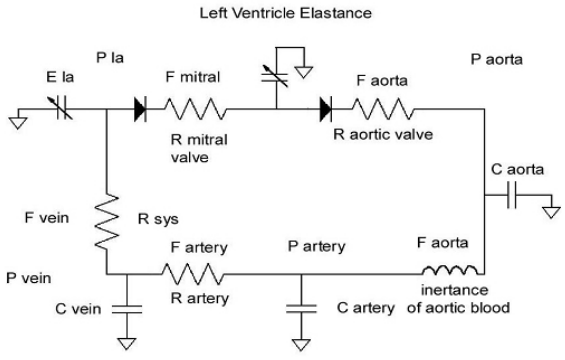


Figure 2. Schematic of the JSim model of the circulatory system. The labels are P for the pressure values, F is the flow, R is the resistance, C is the compliance and L is the inertance at the given locations shown above.

for systolic contraction in the model.

The JSim model of the human systemic circulation was composed of a varying elastance LV and LA tied to a systemic arterial, capillary and venous system in a closed loop (Fig. 2). [5] Elastance is a time-varying stiffness parameter in the relationship of left ventricular pressure P(t) to ventricular volume V(t).

The coupled analysis process begins with the optimization of the diastolic LV pressure volume values to those of the FE model. Following this optimization, the JSim model is run allowing the elastance parameters of the model to reach equilibrium (~5 cycles). At four time points during systole, using the steady-state time-varying solutions of the JSim model, the values for the LV pressures (Fig.3) and volumes (Fig.4) were recorded. The four sets of values from JSim's 1-D circulatory model (times, LV pressure and volume) were provided to the NIKE3d FE simulation. Figure 5 provides a schematic of the coupled analysis process. At each of the four systolic time points, the volume output of the FE model was optimized by adjusting the active contractile stress until pressures and volumes matched those provided by JSim's circulatory model. This resulted in a parameterization of an FE model with constrained time-dependent physiological outflow impedance, and a 1-dimensional equivalent model running under JSim defining systemic arterial pressures and flows.

Coupled analysis was performed on two cases. The first was a normal LV model under normotensive loading (116/80 mmHg). The diastolic and subsequent systolic optimizations were made on the parameters determined from a previously developed model. [6] The second case was the same model under mild hypertension (165/90 mmHg) loading. In this case, the optimized normal model was used as the starting point for the hypertension optimization. The curves labeled "starting values" in Figure 6 are the NIKE3d volume values on the initial trial following the substitution of the JSim pressure values into the NIKE3d model. Four iterations led to convergence at each of the time points.

Upon completion of the optimizations, the first principal stresses for the two finite element models were compared. The pressure volume loops for the coupled models were compared for the normal and the hypertensive cases.

## 3. Results

The diastolic optimizations were completed for both cases in relatively short time, 5 minutes for 150 iterations using the sensop optimizer [7] run on a four processor Linux computational server. The optimized diastolic pressure values fell within 1.0 mmHg of the NIKE3d target values and the end-diastolic volume fell within 1.5 ml. of the target values for both cases.

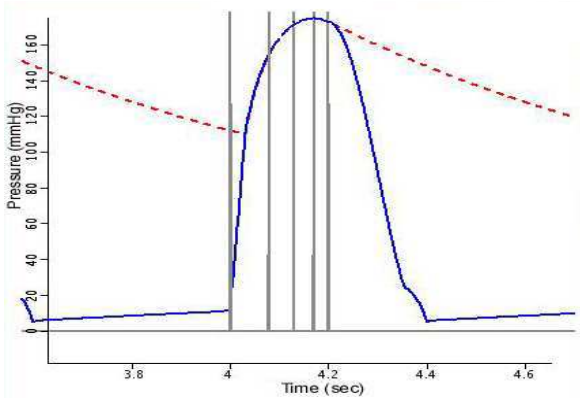


Figure 3. JSim derived LV pressure curve (blue) used in the optimization. Aortic pressure curves (red dashed). The vertical arrows indicate the diastolic and four systolic time points used in the optimizations.

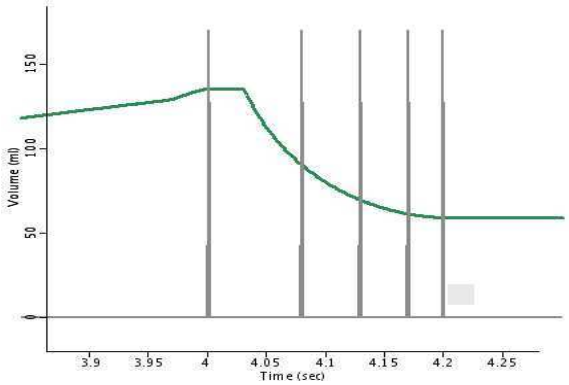


Figure 4. JSim derived LV volume curve (green) used in the optimization. Optimization points are indicted in gray. This is the hypertension pressure curve.

The systolic optimization for the four systolic time points (Fig. 3 and 4) required four NIKE3d iterations (Fig. 6) for each step showing relatively quick convergence in both the normotensive and the hypertensive cases. The total analysis time was approximately 8-9 hours on the Linux computational server. The starting pressure values for the systolic optimization, for example, gave an initial volume at 530 msec that was substantially too low, while the initially computed volumes at 565 and 600 msec were much too high, thus requiring the iterative calculation to achieve convergence (Figure 6, upper panel). In contrast, using the optimized results from the normotensive case as the starting point for the hypertensive case gave a better initial step, due to the more physiological starting point, and rapid convergence was achieved (Figure 6, lower panel).

The finite element calculations give an estimate of the myocardial stresses. In the normotensive case, the

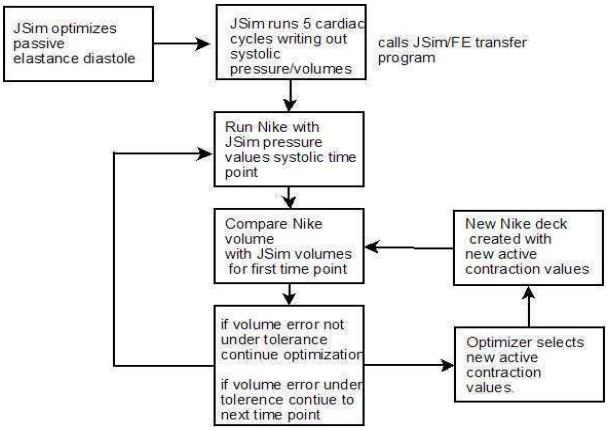


Figure 5. Schematic of the coupled system analysis. The first step in the process is the diastolic optimization. This is followed by the optimizations for the four systolic time points.

average first principal stress was 39.1 KPa while in the hypertensive case it was 51.8 KPa. This represents a 32% increase in end-systolic stress.

The pressure volume loop for the LV in this coupled system model shows a larger stroke volume in the hypertensive case (Fig. 7), nearly twice that of the normotensive case.

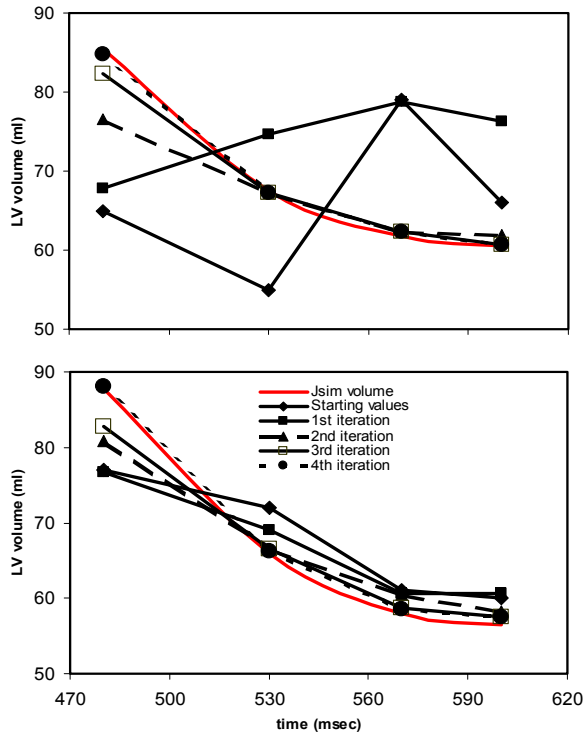


Figure 6. Systolic optimization results for the four iterations necessary for convergence in the (top) normo-tensive case and (bottom) the hypertensive case).

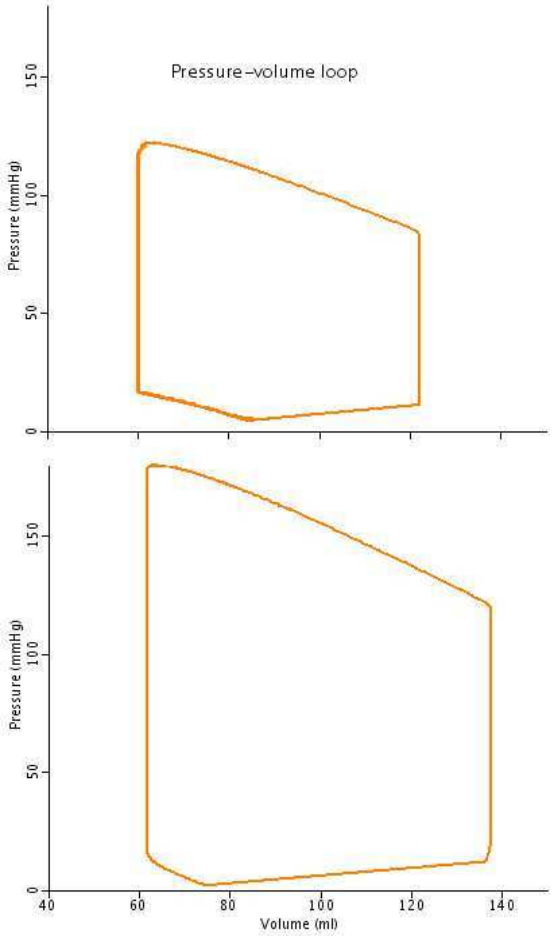


Figure 7. Steady State pressure volume loops for the (top) normotensive circulation model and the (bottom) hypertension model.

## 4. Discussion and conclusions

The analysis of the normotensive and the mild hypertensive cases indicate that even relatively mild hypertension can cause a marked increase in total LV work load as demonstrated by the first principal stress results, and the area of the PV loops.

The methodology presented in this paper demonstrates a relatively simple coupling of a 1D circulatory model with a 3D finite element model of the left ventricle. The type of coupled system is relatively flexible and did not require any alterations to the underlying source code for either JSim or NIKE3d.

The primary limitation of the current implementation is that the transfer of information is unidirectional at the diastolic and four systolic time points. The diastolic pressures and volumes are passed from the NIKE3d model to the JSim analysis in order to tune the circulatory system to the passive mechanics of the LV model. Similarly, the systolic pressures and volumes are passed

from the JSim 1D circulation analysis to the NIKE3d optimization at the four systolic time points. With this type of restricted information flow, the types of pathologies that can be analyzed are limited to circulatory based issues such as hypertension. The communication necessary for heart failure and ischemia/infarction would need to be bi-directional at both the diastolic point and the systolic points so that the deficiencies in cardiac function will alter the response of the circulation. This type of bi-directional communication is currently under development.

The circulatory system model is also overly simple. There is a lack of a dicrotic notch in the aortic pressure waveform (Fig. 3) and the pressure/volume waveform representing systolic contraction is too angular compared to those measured in vivo. In general the maximum aortic pressure occurs earlier relative to the closure of the aortic valve rather than almost at closure as shown in the figure.

The concept of this type of coupling has been demonstrated in the work of Kerckhoffs et al. [8] who have imbedded a 1-D circulatory system into the Continuity simulation package [9] in order to provide the appropriate boundary conditions to a 3-D finite element based right and left ventricle (LV) model. The primary difference in the two methodologies is that the Continuity based analysis represents a single simulation package dedicated to this type of cardiovascular analyses. In contrast, our work demonstrates the coupling of two completely separate simulation packages. In this manner, other types of coupled analysis between JSim based models and NIKE3D based finite element analyses are possible using the information transfer software developed for this project.

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[9] Continuity modeling environment. www.continuity.ucsd.edu.

Address for correspondence

Name Alexander Veress
Full postal address
Department of Mechanical Engineering, Box 352600
Seattle, WA 98195, USA
E-mail address averess@u.washington.edu