# Cardiac Tissue Remodeling During Long Duration Space Travel and Heart Failure

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***Abstract* - We have designed a computational model of the left ventricular function of the heart and its aortic outflow system in order to assess the heart's response during pathological conditions such as heart failure. It is believed that our model of may be applied to identify conditions that can help to reverse cardiac adaptation to eccentric hypertrophy while astronauts experience microgravity.**

## I. BACKGROUND

Eccentric cardiac hypertrophy is usually considered a condition that may lead to the development of additional pathologies; for example, it can cause fatal arrhythmias to develop in affected patients, as well as ventricular outflow tract abnormalities that may cause thrombosis. By LaPlace's Law, the geometry of the ventricles is an important factor in determining cardiac wall stresses[1]. Exposure to microgravity may result in cardiac remodeling during extended spaceflights, which causes the ventricular myocardium to hypertrophy in an attempt to normalize wall stress and thereby optimize cardiac function[1]. While this is compensatory in the short term, the myocardium eventually becomes incapable of meeting the increased work load; this leads to heart failure in the long term[2]. Previous research by NASA has indicated that spaceflight causes a suite of negative health effects, which become more problematic as crew members stay in orbit for long periods of time[3]. While data is being collected on the International Space Station to help elucidate these effects and how to prevent them, it is in our astronaut's best interests to study these effects in other ways as well.

## II. METHODS

The left ventricular function of the heart, along with its aortic outflow system, can be modeled as a series of equations as follows:

(1) $\text{Contractility}(k,\omega,t) = \frac{1}{2}k\left(1+\cos(\omega t)\right)$

(2) $P_{venous}(t) = \frac{V_{total} - \rho_{blood} * g * h_{Iliac} * C_{Iliac}}{C_{Vena\ Cava}}$, where C=compliance

(3) $P_{Left\ Ventricle\ (LV)}(t) = (V_{LV}-V_0) * \left(1 - \left(\frac{V_{LV}}{25}\right)^2\right) * \text{Contractility}(k,\omega,t) + \frac{V_{LV}-V_0}{C_{LV}}$

(4) $V'_{LV}(t) = \frac{P_{venous}-P_{LV}}{\begin{cases} R_{mitral}, & P_{venous}-P_{LV}>0 \\ x*R_{mitral}, & P_{venous}-P_{LV}<0 \end{cases}} - \frac{P_{LV}-P_{aorta}}{\begin{cases} R_0, & P_{LV}-P_{aorta}>0 \\ x*R_0, & P_{LV}-P_{aorta}<0 \end{cases}}$

(5) $P'_{aorta}(t) = \frac{1}{C_{aorta}} * \left( \frac{P_{LV}-P_{aorta}}{\begin{cases} R_0, & P_{LV}-P_{aorta}>0 \\ x*R_0, & P_{LV}-P_{aorta}<0 \end{cases}} - \frac{P_{aorta}}{R_{systemic}} \right)$

In order to model the geometry of the left ventricle and its effects on wall stresses, the following series of equations was developed where h describes the left ventricular wall thickness, r is the radius of the left ventricle, ts and td are time constants, and σ is the wall stress:

(6) $\text{Average Midwall Stress } (\sigma_m) = \frac{PR_i}{2h}$

(7) $h'(t) = \frac{1}{ts}\left(\frac{P*r(t)}{2h(t)} - \sigma_{S_0}\right)$

(8) $r'(t) = \frac{1}{td}\left(\frac{P*r(t)}{2h(t)} - \sigma_{d_0}\right)$

Mathematica's numerical differential equation solver was utilized to compute the desired outputs. The constants that were used in the calculations for cardiac geometries are tabulated in Table 1 below.

## III. RESULTS

By evaluating the pressure-volume relationship under patient specific conditions, the basis of cardiac dysfunction can be elucidated. One of the inputs to our model includes the effects of gravity on venous return to the heart. It is believed that the heart hypertrophies under microgravity conditions and this can

TABLE 1

| **Constants for Heart Geometry Calculations[2]** | |
|---|---|
| | **Value** |
| **Mid Wall Radius** | 2.4 cm |
| **Wall Thickness Under Normal Conditions** | .85 cm |
| **Wall Thickness Under Pressure Overload Conditions** | 1.6 cm |
| **Wall Thickness Under Volume Overload Conditions** | 1.1 cm |
| **Peak Systolic Pressure Under Normal Conditions** | 117 $10^3$ dyne/cm$^2$ |
| **End Diastolic Pressure Under Normal Conditions** | 10 $10^3$ dyne/cm$^2$ |
| **Peak Systolic Pressure Under Pressure Overload Conditions** | 220 $10^3$ dyne/cm$^2$ |
| **End Diastolic Pressure Under Pressure Overload Conditions** | 23 $10^3$ dyne/cm$^2$ |
| **Peak Systolic Pressure Under Volume Overload Conditions** | 139 $10^3$ dyne/cm$^2$ |
| **End Diastolic Pressure Under Volume Overload Conditions** | 24 $10^3$ dyne/cm$^2$ |
| **Time Constant For Systole** | 108,000 mins |
| **Time Constant For Diastole** | 108,000 mins |

lead to cardiac dysfunction after long term exposure. The results of our model compare well with physiological behavior as intended. The pressure and volumetric calculations are able to model this, and the heart geometry calculations serve to validate this fact.

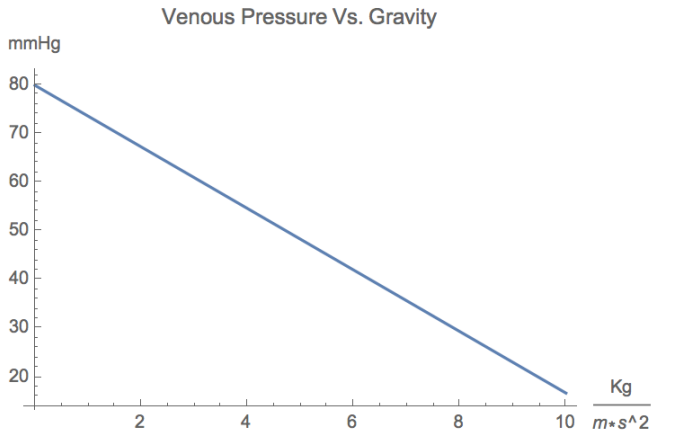


Fig. 1. Graph showing the venous pressure dependence on gravity. As gravity increases, the pressure of venous return to the heart decreases as the column of blood is forced down. Low gravity conditions (i.e. microgravity experienced by astronauts) result in greatly increased venous pressure, leading to unwanted stress being placed on the heart.

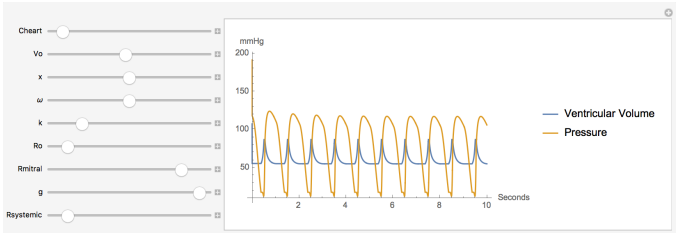


Fig. 2. Plot of ventricular pressure and volume versus time on the same set of axes. Many of the parameters used within the model can be manipulated real-time (as seen by the sliders on the left of the graphic), and their effects of both pressure and volume can be seen on this graph. The opening and closing of the heart valves can clearly be seen as well.

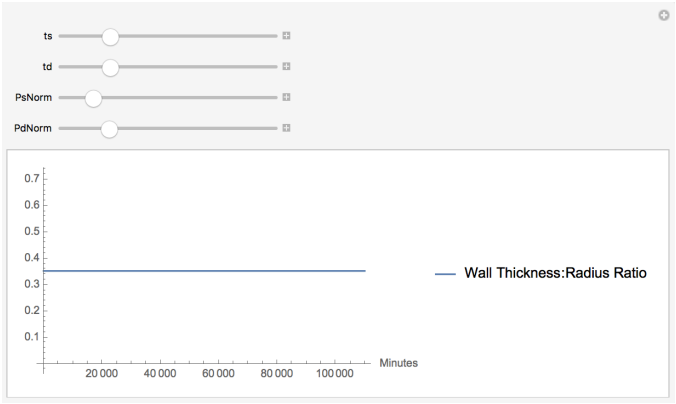


Fig. 3. Plot showing the wall thickness to radius ratio of the left ventricle. While these parameters can be visualized independently of each other, analyzing their ratio can help distinguish between cases of pressure overload and volume overload[2]. The parameters shown above are under normal conditions, but manipulating them to either pressure or volume overload levels shows a shift to pathological values.

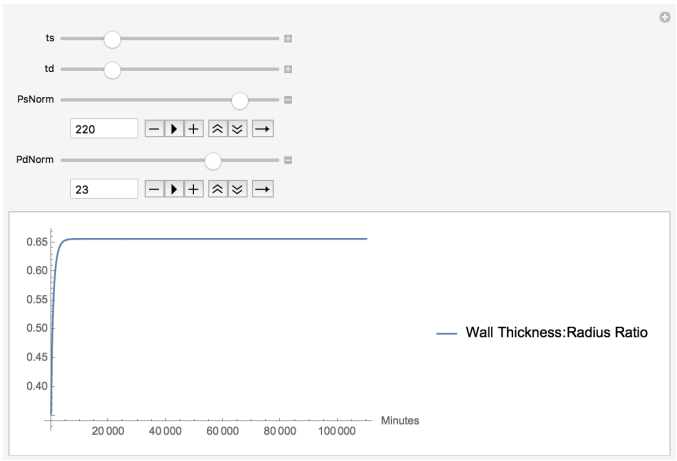


Fig. 4. Plot depicting the progression from a healthy wall thickness to radius ratio to an elevated level as a result of pressure overload conditions[2].

## IV. CONCLUSIONS AND DISCUSSION

By evaluating the pressure-volume relationship under patient specific condition, the basis of cardiac dysfunction can be elucidated. One of the inputs to our model includes the effects of gravity on venous return to the heart. It is believed that the heart hypertrophies under microgravity conditions and this can lead to cardiac dysfunction after long term exposure[4]. Our growth model is based on left ventricular wall stress normalization, and the results of our model compare well to other metabolic type growth models[4] in that it can predict eccentric and concentric hypertrophy in patients[2]. Shortcomings of the model include the inability to show the effects of cardiac hypertrophy in the long term and a progression from a healthy to a sick heart. To address the first issue, we looked at changes in cardiac geometry. This allowed us to look at changes in the heart over a longer period of time. We plan to address the second issue by relating the long term changes in geometry to a change in compliance of the heart, which will allow us to integrate the two portions of our code to show a progression towards pathological conditions; fig. 4 depicts such a progression.

## VI. ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding received for this research from the NJSGC in 2016.

## V. REFERENCES

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