

Influence Of Microgravity On Left Ventricular Sphericity: A Finite Element Model Of The Heart

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There is concern regarding the effects of microgravity exposure on cardiac function and loss of ventricular mass in astronauts. By Laplace's law, the geometry of the ventricle is important in determining segmental wall stress and can induce alterations in myocardial mass. If microgravity exposure results in a variation in the ventricular radius of curvature, then we might also expect some cardiac remodeling during extended spaceflights. This study analyzes the theoretical impact of microgravity on changes in the geometric conformation of a finite element mesh model (FEM) created from the 3-dimensional geometry of the human left ventricle (LV) and attributed with material properties consistent with myocardial tissue. The Geometric Aspect Ratios (GAR, length to width quotient) of the LV were calculated and compared during simulations of the upright anatomic diastolic position in Earth's gravity and in microgravity. The theoretical application of microgravity to the FEM model of the heart resulted in a 3.65% lower GAR of the LV as compared to that calculated for Earth's gravity. This finding suggests that microgravity exposure could potentially result in changes in ventricular sphericity and radius of curvature and thereby alter the segmental myocardial wall stress.

Nomenclature

FEM = finite element mesh model
LV = left ventricle
GAR = Geometric Aspect Ratio, length to width quotient

I. Introduction

Physiologic and anatomic adaptations to microgravity exposure are considered one of the greatest barriers for human space exploration.¹ One of the most concerning of these changes is the 10-15% diminution in left ventricular mass that has been observed in astronauts.^{2,3,4} While some of these recorded changes in the myocardial volume can be attributed to simple fluid shifts, there appears to be a true loss of ventricular muscle mass when the exposure to microgravity is prolonged.^{3,5,6} The mechanism responsible for this loss of myocardial muscle is uncertain. While intuitively it could be assumed that the heart would work less in microgravity and result in an attrition of muscle mass, there is no convincing evidence to support this notion. Commonly measured hemodynamic parameters such as heart rate, blood pressure and cardiac output appear to be clinically near normal during spaceflight so it has been difficult to determine a driving force for the observed degree of cardiac atrophy.^{7,8,9,10,11}

A recent study demonstrated a linear relationship between the sphericity in the geometry of the left ventricular chamber as measured by echocardiography and the amount of gravitational forces in the environment.¹² It appears that the ventricles can be considered as fluid filled malleable vessels that are susceptible to the usual influences of environmental physical forces. During conditions of free fall or without the downward pull of gravitational forces,

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the ventricular chambers are thought to tend to become more spherical in their geometric conformation due to an equilibration of wall surface tensions.

The significance of this finding becomes clear when the resultant differences in myocardial wall tension forces induced by these changes are considered. In accordance with Laplace's law, the geometry of the ventricle is an important factor determining tension and segmental wall stress.^{13,14} The wall stress of any segment of the myocardium is therefore highly dependent upon the local geometry, particularly the radii of curvature of the ventricle wall at that location.¹⁵ It is thought that the ventricular myocardium hypertrophies or atrophies in an attempt to normalize wall stress and thereby optimize cardiac function.¹⁶ Such changes have been observed clinically in patients with valvular disease and other chronic pathologic conditions where the ventricles assume a more spherical shape.^{13,17,18} If microgravity exposure primarily induces alterations in local ventricular geometry and wall stress through conformational changes in the overall shape of the heart, then a general remodeling of myocardium might also occur. This mechanism could provide a possible explanation for the physiologic adaptation of the heart to its gravitational environment that is based upon simple physical forces as described by Laplace's Law.

In this study a finite element model (FEM) of the left ventricle (LV) attributed with material properties consistent with myocardial tissue was used to examine the theoretical impact of microgravity on changes in the overall geometric conformation of the heart.

II. Methods

Mimics, 3-matic software and Simpleware software were used to create a mesh model of the heart for finite element analysis. Three different mesh models of varying qualities (voxel mesh, low tetrahedral, and normal tetrahedral) were exported to ABAQUS for comparison of the finite element analyses. The heart tissue was considered as an isotropic material for simplification and myocardial mechanical material properties were incorporated into the elements of the mesh. The biaxial mechanical properties of tissue extensibility and tensile modulus used in the study were derived from published the literature.¹⁹ These properties have been characterized with a biaxial mechanical testing system in a square specimen trimmed from a native porcine myocardium engineered cardiac patch. In this preparation, biaxial loading was applied along the muscle scaffold fiber direction and cross-fiber directions of the specimen.

A series of simulation studies were carried out investigating changes in heart shape deformation in earth's gravity and during microgravity exposure. In the simulations, the model heart was situated in the anatomical position as if the person were standing, and the force of gravity (9.81 m/s²) and microgravity (1.0e-⁶ m/s²) were implemented vertically downward on the heart. The heart was also considered in the unpressurized state and without blood filling in the chamber in order to discern the independent impact of gravity on the heart tissue. The length and width of the left ventricle were recorded to calculate geometric aspect ratios (GAR) as an indicator of relative sphericity (equation below) and to assess the extent of global heart shape deformation in gravity and microgravity.¹²

$$\text{Geometric Aspect Ratio} = LV \text{ length} / LV \text{ width} \quad (1)$$

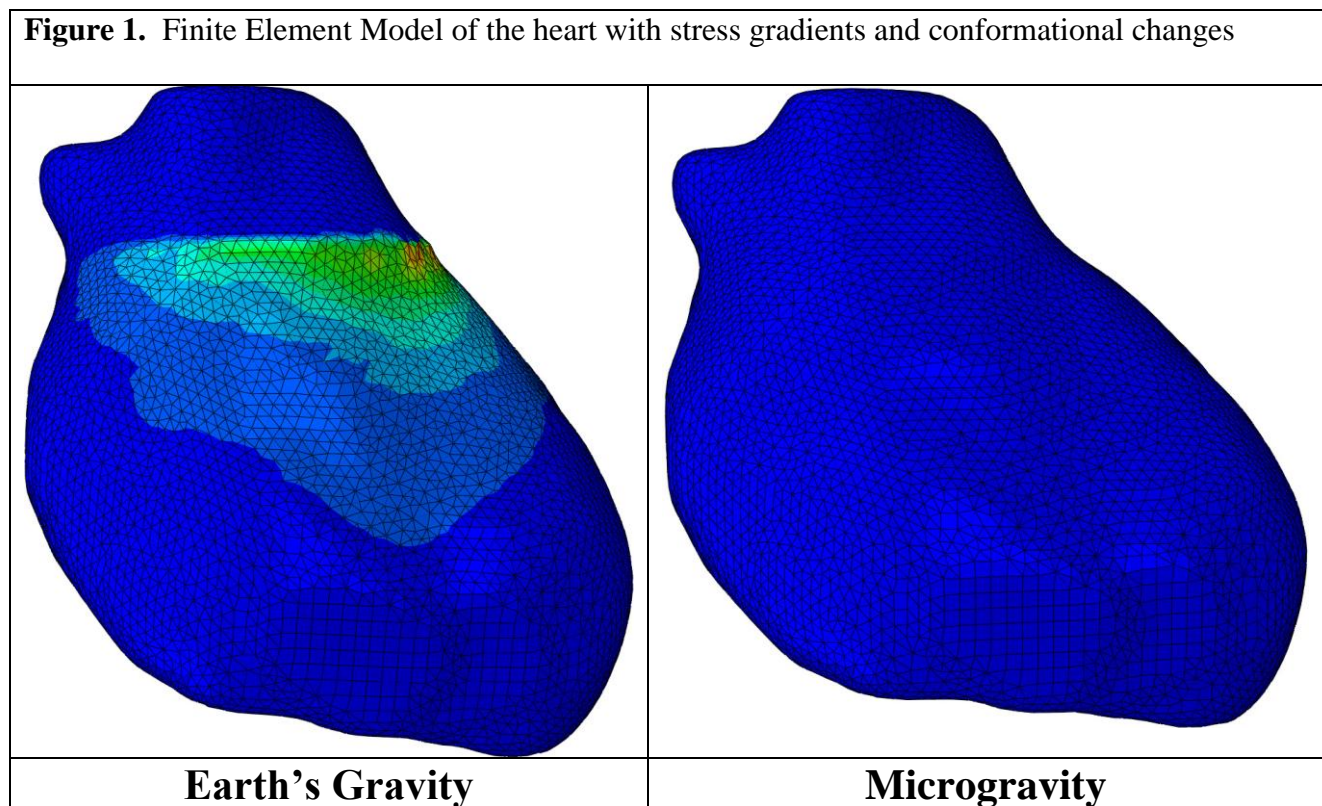
The LV sphericity index was calculated by dividing the LV maximal long-axis internal dimension by the maximal short-axis internal dimension at end-diastole. The percent change in the GAR of the FEM determined during simulations transitioning from the earth's gravity to microgravity was calculated.

III. Results

Table 1 details the changes in values in length and width of the unpressurized left ventricle determined in the FEM analysis for both the microgravity and Earth's gravity states. The length of the unloaded ventricle is found to retract by 3.005% while the width expands slightly (0.55%). These changes resulted in an overall increase in the geometric aspect ratio of 3.65% as a global measure of the extent of alteration in the shape of the heart (Figure 1).

Gravity Condition	Length (mm)	Width (mm)	GAR
Microgravity	135	62.3122	2.16
Earth's Gravity	139.0563	61.9484	2.24
Percent Change	-3.005 %	+0.55 %	3.65 %

Table 1. This table depicts the values for changes in LV length,width and geometric aspect ratio (GAR) determined in the FEM analysis for both the unloaded (microgravity - $1.0e^{-6}$ m/s²) and loaded (Earth's gravity - 9.81 m/s²) states. The length is found to retract by over 3% while the width expands slightly when the heart is unloaded. These changes results in an overall increased in the geometric aspect ratio of 3.65%.



IV. Discussion

The impact of microgravity exposure on physiologic and anatomic adaptations is probably the greatest barrier to the human exploration of space. The development of effective countermeasures to these adaptations requires a clear understanding of the biologic mechanisms driving the observed changes. In the current study, we provide a theoretical analysis using a FEM of the heart to explore the feasibility that a microgravity environment might generate conformational changes in the heart. The intent of the analysis is to provide support for the hypothesis that microgravity induced shape changes in the LV and their resultant changes in myocardial wall stress are a potential mechanism leading to a diminution in LV mass in astronauts. The mechanisms responsible for the changes in LV mass seen during spaceflight are probably multifactorial and can involve variations in workload, sympathetic inputs and a number of other influences that act synergistically. However, the complexity of this problem could potentially

benefit from the perspective of a simple theoretical framework employing basic physical factors from which to develop a more comprehensive mechanistic hypothesis concerning ventricle remodeling in varying gravitational environments.

There is considerable evidence indicating that there is a direct relationship between ventricular wall stress and the extent of myocardial hypertrophy in chronic pathologic states such as hypertension and cardiac valvular disease.^{13,17,18,20} Conventional wisdom suggests that the ventricular myocardium hypertrophies in an attempt to normalize wall stress and thereby optimize cardiac function.¹⁶ Since hypertrophy and atrophy of muscle begins at the cellular level it can be assumed that the stress factors driving these morphologic changes are also of a regional or segmental nature. The wall stress of any segment of the myocardium is highly dependent upon the local geometry as characterized by the radii of curvature of the ventricle wall at that location.^{14,15} Decrease in the segmental wall stress has been observed clinically in patients with valvular disease and other chronic pathologic conditions where the ventricles assume a more spherical shape.^{13,21,22} The current analysis indicates that microgravity could induce similar alterations in this local wall geometry through changes to the overall shape of the heart. If such conformational changes are found to occur in astronauts during spaceflight, then this could provide a driving mechanism for the observed cardiac remodeling that is based upon simple physical forces as described by Laplace's Law.

There are several limitations to this study that should be noted. The material properties used for the cardiac tissue were derived from a porcine study performed on earth and may not accurately reflect those of the human heart in space. The FEM analysis also examined the effect of gravity on the heart in isolation from the rest of the body. However, the 3.65% change in GAR found in the current study seems reasonable when compared to the 5.3% change noted in a small sample of astronauts during spaceflight.¹² The unpressurized initial conditions used in the FEM analysis could account for the observed differences. A physiologic negative extramural pressure, positive diastolic intraventricular pressure and hydrostatic gradients within the upright ventricle earth's gravity would all amplify the differences seen between microgravity and earth gravity conditions. It is important to note that a number of ancillary factors (i.e. diaphragm movement, lung volumes, fluid shifts) could also be involved in the determination of shape of the human heart during spaceflight. The intent of the present study was simply to determine if a significant conformational change in the global heart shape could be attributed to a loss of gravity influence alone. Such a shape modification and the resultant changes in the ventricular wall regional radii of curvature are central to the proposed hypothesis of a cardiac remodeling directly induced by wall stress changes resulting from microgravity exposure. Future study should include greater anatomic detail, the impact longitudinal gravitational gradient of the blood, pressurized cavities, extramural pressures, influence of the diaphragm, anisotropic layer myocardial muscle, and calculations of regional curvature and wall stresses.

The significance of a 3-5% shape change toward sphericity as it relates to cardiac remodeling is uncertain. A similar analysis by Herrold and Borer has predicted that clinically important ventricular remodeling can be induced by comparable spherical changes resulting from conditions of chronic volume overload as seen in valvular disease.²³ Such remodeling is also a common occurrence in other cardiac pathologies in which the shape of the heart is changed.^{18,20,22} However, intracardiac pressures in these conditions may in addition be significantly changed and influence remodeling. Even though end-diastolic pressure is relatively low and does not usually exert significant forces on the myocardium, changes in this pressure may be more important than the impact of changes in curvatures. However, there is no definitive evidence to conclude that end diastolic pressure is significantly changed in microgravity, especially since stroke volumes, heart rates and cardiac output appear to be near normal.^{7,8,9,10,11}

Beyond the influence that a change in heart shape might have on myocardial tissue volume, there may also be a direct and independent impact on global cardiac function. There is evidence suggesting that the shape of the heart is important in determining the efficiency of the twisting motion of the ventricles, particularly as it relates to their diastolic function.²⁴ Furthermore, recent spaceflight and long-term head down tilt bed rest studies used to simulate microgravity exposure have likewise demonstrated impairments in diastolic functioning due to inefficiencies with untwisting.^{25,26} Systolic function may also be dependent upon regional and global wall curvatures.²⁷ Myocardial shape changes and the possible resultant remodeling have also been implicated in the development of cardiac dysrhythmias.^{28,29,30} Such dysrhythmias have been observed during spaceflight.⁵

V. Conclusion

It has been suggested that the loss of ventricular mass in astronauts may be a result of changes in heart shape during microgravity exposure.^{3,12} Currently there is no direct causal evidence to support a conclusion that cardiac conformational changes during spaceflight result in reductions in LV mass or alter cardiac function. However, in accordance with Laplace's law, the geometry of the heart and its impact on the segmental wall stress should act as a driving force for cardiac remodeling. This study examined the theoretical impact of microgravity exposure on the shape of the LV.¹³ Changes in ventricular sphericity associated with changes in the radius of curvature of the myocardial wall of an FEM model were observed during simulated microgravity. Further study is required to absolutely link the observed loss of myocardial mass in astronauts to accompanying ventricular conformational changes. The intent of this study is simply exploratory to provide further evidence that significant LV shape changes might occur when the heart is exposed to microgravity and stimulate further investigation of this potential contributing factor in future studies concerning LV adaptations to microgravity exposure.

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