A FINITE ELEMENT MODEL OF THE HUMAN VENTRICLES FOR THE RAPID FILLING PHASE DURING EARLY DIASTOLE

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Introduction

The analysis of the stress-strain pattern of the myocardium during the cardiac cycle is aimed at elucidating the mechanics of the heart under physiologic and pathologic conditions. Under the pressures occurring in this muscle, the passive fluid-filled myocardial tissue can be considered as incompressible. Furthermore the ventricles are submitted to large deformations during the heart cycle.

During ventricular systole, large amounts of blood accumulate in the atria because of the closed atrioventricular valves. After the isovolumetric relaxation period, at the end of which the ventricular pressures approach their diastolic values and the pressures in the atria are moderately increased due to venous return, the tricuspid and the mitral valves open. As the myocardium returns from the contracted to its resting state, the blood is immediately sucked into the ventricles, i.e., it flows rapidly from the atria into the ventricles and their volumes increase quickly. This is denoted as the rapid filling phase and represents about the first third of diastole. During the middle third only a small amount of blood flows into the ventricles, corresponding to the momentary venous return reaching the ventricles through the atria. The rise of the ventricular volumes is small. Finally the atria contract and give an additional thrust to the ventricular blood filling. This period is called the atrial systole. It corresponds to about 25% of the filling phase.

It is during the first third of diastole that the ventricular pumping effectiveness is the most important. This period plays an important role during the diastolic phase. A Finite Element (FE) analysis of the rapid filling phase for the left ventricle has been performed, taking into account the ventricular sucking effect.

Model

In this study the geometry of the left ventricle was approximated to a stretched thick-walled spheroid. Our FE model consisted of 400 parabolic 20-nodes hexahedral, yielding some 7000 degrees of freedom. The myocardium was thereby considered as a homogeneous, isotropic, incompressible material. The study was performed under the assumption of linear elasticity allowing for large deformations. The stresses-strains relation is described by the Kirchoff-St. Venant law:

\[ S_{ij} = \lambda \cdot \text{Tr}(\varepsilon) \cdot \delta_{ij} + 2 \cdot G \cdot \varepsilon_{ij} \quad (1) \]

Where \( \lambda \) and \( G \) (elastic shear modulus) are the Lamé coefficients and are related to the Young modulus \( E \) and the Poisson’s ratio \( \nu \).

In this study the Young modulus was set to 10 kPa [1] and the myocardium’s incompressibility was simulated with a value near 0.5 for the Poisson’s ratio.

To simulate the ventricular sucking effect in the rapid filling phase it was necessary to determine the restoring forces acting in the myocardium during this process. For this purpose a negative pressure of –1150 Pa was first applied on the surfaces of the elements representing the endocardium in its relaxed state where the internal volume of the ventricle is 86.5 ml (as measured by Magnetic Resonance (MR) Imaging [2] at the end of the rapid filling phase). Under the influence of this negative pressure, the
volume reduced to 40 ml, representing the beginning of the diastolic phase [2]. Figure 1 A shows the geometry of the model before the contraction.

Then the contracted geometry (Figure 1 B), having an internal volume of 40 ml corresponding to the end-systolic ventricular volume and obtained after the FE calculation described above, is taken as original geometry for the simulation of the rapid filling phase. The sucking effect is taken into account by applying the values of the internal stresses calculated before to each integration point of the elements. Furthermore, in both analyses for all nodes at the base the degree of freedom in the long axis direction was suppressed, as well as the degrees of freedom perpendicular to the long axis direction for the nodes of the apex.

Figure 1: A) Geometry and mesh of the model before the contraction analysis. Its internal volume is 86.5 ml. B) Contracted geometry with an internal volume of 40 ml.

As an illustration in figure 2 it is visualised the FE model of the human right and left ventricles, based on earlier work [3, 4]. It contains 3835 parabolic 20-nodes hexahedral and 10-nodes tetrahedral elements. The human heart’s geometry was derived from MR measurements, where 32 short axis slices from the apex to the base were taken at end-systole [4].

Figure 2: FE model of the human right and left ventricles

Conclusions

The value for the Young’s modulus chosen here, $E = 10 \text{ kPa}$, is at the lowest end of the values documented in the literature for human myocardium. Nevertheless, a negative pressure of 1150 kPa ($= 10 \text{ mm Hg}$) was necessary to yield a reduction of the volume from 86.5 ml to 40 ml whose opposite is
representative for the rapid filling phase. We conclude, that the passive myocardium exhibits a modulus of elasticity which is considerably below published values.

References