HYPERELASTIC AND VISCOELASTIC FE MODELING OF THE PASSIVE EMBRYONIC TUBULAR HEART IN ABAQUS

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At the onset of contractions, Hamburger-Hamilton stage 9 , the chick embryo heart is a smooth-walled muscle-wrapped hollow tube, lined on the inner side with a thick non-uniform layer of extracellular matrix (cardiac jelly). Soon after the onset of contraction, the morphogenetic process of looping begins. As the wall thickens and the heart grows in size, the tube bends and twists into a curved shape. Looping sets the basic pattern for the final form of the heart. In the chick, this process is nearly completed by stage 16. We use a specialized nonlinear FE formulation to investigate how stresses and strains resulting from ventricular activation and blood pressure modulate growth, morphogenesis, and remodeling during heart looping [1]. To date, our computational model includes the effects of anisotropic growth and contraction in a hyperelastic nonlinear material model. As such, the model is adequate for studying some aspects of the looping process, including initial bending of the heart tube. Experimental studies have shown, however, that the mechanical behavior of passive embryonic cardiac tissue is viscoelastic [2]. Moreover, viscoelasticity (e.g., creep and stress relaxation) likely enables the heart to undergo extremely large deformations during morphogenesis without being damaged.

In order to evaluate the applicability of the quasi-linear viscoelastic (QLV) model adopted by Miller et al. [2] to our hyperelastic formulation, we use simplified cylindrical models of stage 16 and 18 hearts constructed in the commercial code ABAQUS. We consider passive behavior only. Following the QLV assumption, Miller decomposes the total stress T as the product of the hyperelastic response and a relaxation function $G(t) = \dfrac{1 + C\left[E_1\left(t/\tau_2\right) - E_1\left(t/\tau_1\right)\right]}{1 + C\ln\left(\tau_2/\tau_1\right)}$, where E_1 is the exponential integral function, C is the log decay parameter, and τ_1 and τ_1 are the slow and fast time constants respectively. For FE hyperelastic modeling of cardiac jelly and passive myocardium we use the isotropic exponential SED function introduced by Taber [1]. Using incompressibility and isotropy this function is written in terms of the stretch ratio in the radial direction, λ_1, only. Thus, the exponential SED functions for the myocardium and cardiac jelly are curve fitted into ABAQUS as a Yeoh and a Neo-Hookean polynomial, respectively. The relaxation function for 20% strains given in [2] is fitted to a 30 term Prony series available in ABAQUS. FE hyperelastic models representing the stage 16 and 18 hearts are subjected to a 20% axial strain and then allowed to relax viscoelastically under constant displacement conditions. For the stage 16 hearts, the model includes both myocardium and cardiac jelly, while for stage 18 only myocardium is included. Results show an excellent agreement between the ABAQUS model and the experiments. In particular, the stage 16 model indicates that cardiac jelly substantially contributes to the viscoelastic response of the embryonic heart.

References

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