Proceedings of the ASME 2012 Summer Bioengineering Conference
SBC2012
June 20-23, 2012, Fajardo, Puerto Rico

SBC2012-80796

LOWER TRANSIENT STRESSES IN AN AORTIC VALVE LEAFLET WITH OBLIQUE REINFORCEMENT FIBERS: A FINITE ELEMENT STUDY

Peter E. Hammer (1), Robert D. Howe (2), Pedro J. del Nido (1)

(1) Department of Cardiac Surgery
Children's Hospital
Boston, MA, USA

(2) Harvard School of Engineering
and Applied Sciences
Cambridge, MA, USA

INTRODUCTION

Native aortic valve leaflets contain a network of strong collagen fibers within a matrix of relatively distensible tissue. This composite structure leads to anisotropic mechanical properties and is believed to play an important role in the ability of the structure to withstand the stresses of cyclic loading over billions of heart beats. Replacement valves that consist of animal tissues also contain such fibers, but all designs in clinical use are chemically cross-linked, which increases the in-plane stiffness of the tissue and decreases anisotropy. Tissue replacement valves suffer from poor durability due to calcification and tissue degeneration in regions of high stress, including at the base of the coaptation region and at the leaflet commissures [1]. A better understanding of leaflet stresses in these regions and how to mitigate them is important in order to improve the design of replacement heart valves to improve durability.

In previous work, we showed that a trileaflet valve with reinforcement fibers arranged in a v-shaped pattern opening toward the free edge of flexible leaflets can produce an improved seal [2] and allow control of the distribution of leaflet stresses under peak diastolic load [3]. In the present work, we hypothesize that this design has the potential to absorb transient peaks in stress that can arise during valve closure. We use a structural finite element model to compare the effect of different patterns of reinforcement fibers on the temporal changes in stress in the base of the coaptation region of the leaflet during closure of a fiber-reinforced valve. We compute leaflet stresses in and perpendicular to the principal direction of reinforcement fibers as functions of time during the loading cycle.

METHODS

We create a mesh of a generic aortic valve and simulate its deformation using a dynamic structural finite element model. We model the leaflets using three node membrane elements and a hyperelastic constitutive equation. We are interested in simulating fiber-reinforced replacement aortic valves with properties similar to native valve leaflets, so we incorporate a constitutive equation that describes the nonlinear anisotropic in-plane response of the natural aortic valve leaflet [4]. The valve is loaded by transleaflet pressure, and leaflet contact is handled using an efficient method based on axis-aligned bounding boxes and penalty forces. To approximate the effect of blood momentum during valve closure, we used an effective mass density of 42.4 g/cc (40x that of the tissue) to result in a valve closure time equal to the published values of 60-70 ms. We simulate circumferential reinforcement fibers by choosing the first principal direction equal to the direction of the leaflet free edge. The oblique fiber pattern corresponds to a v-shaped pattern of fibers opening toward the free edge, with fibers forming an angle of 25^{o} to the leaflet free edge (Fig. 1).

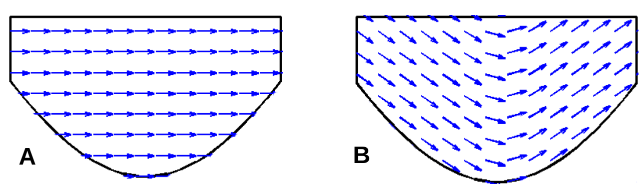

Figure 1 Single leaflet of aortic valve model illustrating patterns of reinforcement fibers. (A) A pattern of straight fibers running parallel to the leaflet free edge is referred to as the circumferential pattern, and (B) a pattern of v-shaped fibers opening toward the free edge is referred to as the oblique pattern.

RESULTS

During simulated valve closure (Fig. 2A), both models of fiber orientation show S_{11} (2nd Piola-Kirchhoff stress in the fiber direction) undergoing a small compressive phase, due to wrinkling/buckling, before climbing to its peak tensile value. For the model with the circumferential fiber pattern, the peak stress is approximately 1.3 times that for the model with the oblique fiber pattern (Fig. 2B). Both models show an initial maxima in S_{22} (2^{nd} Piola-Kirchhoff stress in the direction perpendicular to fibers), but for the model with the circumferential fiber pattern it is followed by a large transient peak (Fig. 2C) coinciding with the deceleration of that leaflet element (Fig. 2D). This results in a maximum value of S_{22} that is 2.5 times that of the maximum for the model with the oblique fiber pattern.

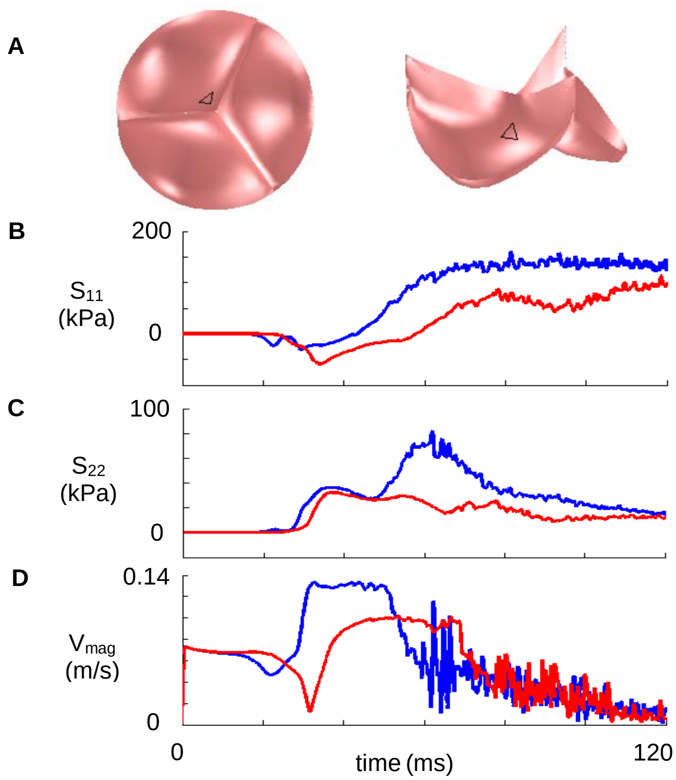

Figure 2 (A) Bottom view (left) and isometric view (right) of model of closed aortic valve at 80 mmHg. Element at which stresses and velocity are measured is indicated by triangle. (B) Second P-K stress in fiber direction versus time. (C) Second P-K stress in direction perpendicular to fibers versus time. (D) Magnitude of velocity versus time. On all plots, blue and red curves correspond to models with the circumferential and oblique fiber patterns, respectively. Note: the high frequency content appearing after 60 ms in all plots is due to the contact handling method utilizing penalty forces.

DISCUSSION

The goal of this study was to explore the possibility that transient peaks in leaflet stress can develop in a critical region of fiber-reinforced valves during valve closure and to see if such transients can be reduced by altering the pattern of reinforcement fibers. Simulation results showed that transients in the stress component perpendicular to fibers can develop in the model with the circumferential fiber pattern. Interestingly, this transient peak in stress occurs in the direction perpendicular to the reinforcement fibers – which is also the direction with the lowest tensile strength.

The transient peak in stress is not present in the model with the oblique fiber pattern. The absence of this peak in stress is likely attributable to a decrease in stiffness in the circumferential direction caused by the oblique fiber pattern. This stiffness decrease follows from the fact that tension in a v-shaped fiber is balanced by membrane tension in the direction toward which the v points (the radial direction in the leaflet). Membrane stiffness is low in this direction, thus circumferential loads on the leaflets are opposed by material with low stiffness for the portion of the leaflet loading phase during which the v-shaped fiber is straightening.

Due to the limitations of using a purely structural model to study valve closure - a process fundamentally linked to fluid dynamics - we are hesitant to draw conclusions that depend on quantitative results of simulation. However, results qualitatively suggest that fiber-reinforced leaflet structures can support transient stresses due to sudden pressure loading and that an oblique fiber pattern can reduce or eliminate these transients through an effective increase in compliance resulting from fiber kinematics.

ACKNOWLEDGEMENTS

This work was supported by NIH grant R01 HL073647.

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