Mechanical Properties of Autologous Pericardium Change With Fixation Time: Implications for Valve Reconstruction

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Autologous pericardium, fixed in glutaraldehyde, is a common patch material used in heart valve reconstruction. Competence of a reconstructed valve depends on patch dimensions and also on how much the patch deforms when the closed valve is pressurized. In this study, we used biaxial testing to evaluate the deformability of fixed autologous pericardium, and several commercial alternatives, under typical cardiac loads. We found that deformability of fixed autologous pericardium varies predictably with fixation time. This information can be used by surgeons in designing patches for valve repair.

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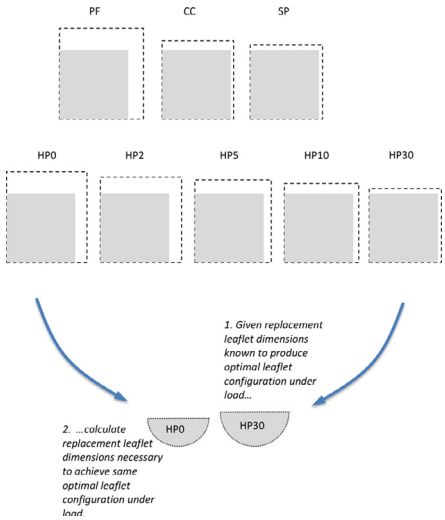
Keywords: Valve reconstruction, Bovine pericardium, Autologous pericardium, Biaxial mechanical testing



Deformation of pericardium under load depends on fixation method and duration.

Central Message

Deformability of fixed autologous pericardium varies predictably with fixation time. This information can help surgeons design patches for valve repair.

INTRODUCTION

Surgical reconstruction of heart valves with leaflet replacement materials has been performed for decades. In children, we typically use autologous pericardium if available, fixed in glutaraldehyde. Competence of a reconstructed valve depends not only on the dimensions of the replacement leaflet or patch fashioned by the surgeon but also on how those dimensions stretch when the closed valve is pressurized. In our experience, surgeons have a general idea that the stretchiness (compliance) of autologous pericardium varies with fixation time and that more compliant materials must be undersized to avoid prolapse under load. However, quantitative guidelines for fabricating replacement leaflets/patches based on fixation time have not been established. Data exist on mechanical properties of human pericardium from uniaxial tests[1]; however, uniaxial data cannot be used to inform how tissues deform under pressure loading.[2] We hypothesize that the compliance of autologous pericardium decreases with glutaraldehyde fixation time, and the objective of this study is to quantify how the deformation (strain) of this tissue varies with fixation time under loads typical in left-sided heart valves. To do this, we performed planar biaxial testing on human pericardium specimens, following various glutaraldehyde fixation times, along with several commercial bovine pericardium products for comparison.

METHODS

All tested biomaterials were discarded specimens collected from the cardiac operating room between March and October 2017. Tested repair materials included: (1) human (autologous) pericardium (AP), (2) PhotoFix bovine pericardium (PF, Cryolife, Kennesaw, GA), (3) CardioCel bovine pericardial patch (CC, Admedus, Minneapolis, Minnesota), and (4) Supple Periguard bovine pericardium (SP, Synovis, St. Paul, MN). Harvested AP was either untreated or bathed in 0.625% glutaraldehyde solution for 2, 5, 10, or 30

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minutes. Testing was performed using a biaxial tester (Biotester, CellScale, Waterloo, Canada). Principal material direction (ie, predominant collagen fiber direction) and tissue thickness were determined for each specimen (Supplementary Methods, Fig. S1). Specimens were tested over a range of biaxial loads intended to approximate physiologic loads for left-heart valves (Fig. S2).

RESULTS

All materials exhibited nonlinear anisotropic mechanical response to equibiaxial tension (Fig. 1). Under typical working loads, specimens of untreated AP underwent mean stretch of 17% and 32% in the principal material direction and the direction perpendicular, respectively (Table 1). Increasing fixation time of AP uniformly decreased the stretch in both material directions; after 30-minute fixation, mean stretch was 4.7% and 7.0% in the respective material directions. The response of SP was similar to AP treated for 30 minutes, although SP exhibited less variability. The response of PF was similar to untreated AP, although the slopes of the stress-strain curves were lower for PF than for untreated AP (Fig. 1).

DISCUSSION

Our primary finding of decreasing compliance in AP with increasing glutaraldehyde fixation time is not surprising.

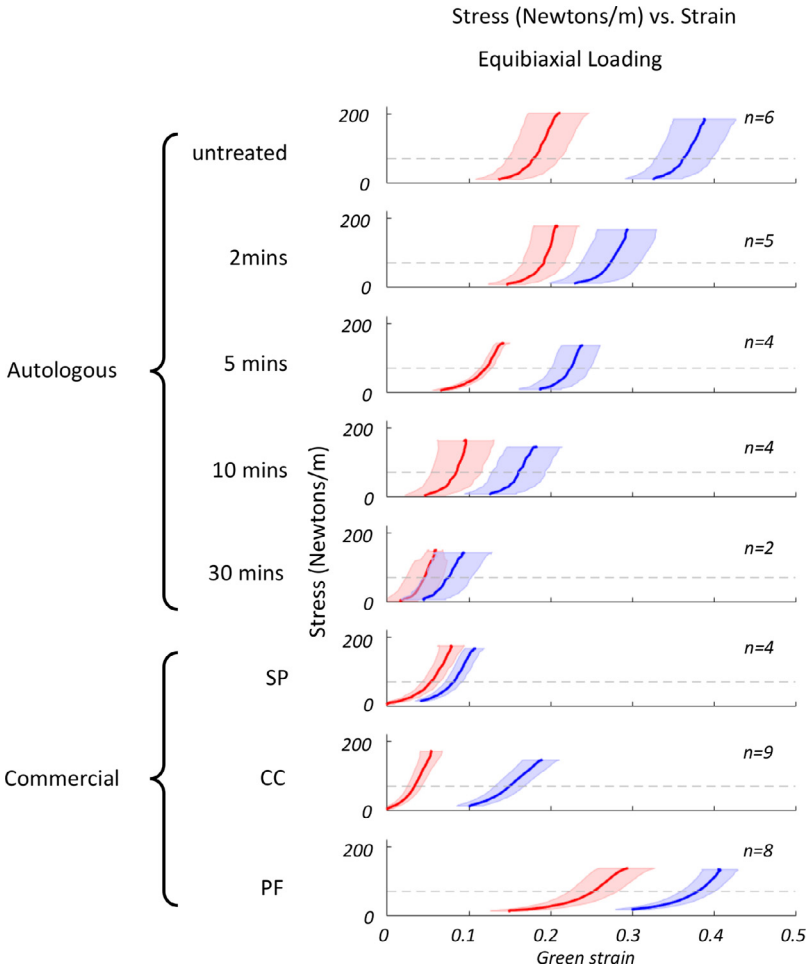


Figure 1. Stress vs strain for human (autologous) pericardium and for 3 commercial bovine pericardium products: Supple Periguard (SP), CardioCel (CC), and PhotoFix (PF). The autologous pericardium specimens were treated with glutaraldehyde in the operating room for durations indicated prior to testing. Stress is expressed as second Piola-Kirchhoff membrane tension (Newtons/m) and is a measure of the load borne by the tissue. Strain is expressed as Green strain (unitless) and is a measure of how much the tissue deforms (stretches) in response to the load. (For example, a strain of 0.10 corresponds roughly to a stretch of 10%). Plots for the principal material direction and perpendicular direction are shown in red and blue, respectively, and the corresponding shaded regions depict standard error. The number of specimens tested appears in the upper right of each plot. The value of membrane tension corresponding to a typical load on left-sided valves (70 Newtons/m) is shown by the dashed line.

Table 1. Tissue Stretch in the Principal Material Direction (λ_1) and in the Direction Perpendicular (λ_2) Under Equibiaxial Tension Corresponding to a Typical Left-Sided Valve Load (70 Newtons/Meter)

Tissue	λ_1 (%)		λ_2 (%)	
HP0	17 ± 7.1	(SP, CC)	32 ± 6.8	(HP5, HP10, HP30, SP, CC)
HP2	18 ± 4.8	(SP, CC)	24 ± 6.1	(HP30, SP, CC)
HP5	11 ± 1.0	(PF)	20 ± 4.1	(HP0, PF)
HP10	7.9 ± 5.9	(PF)	15 ± 5.7	(HP0, PF)
HP30	4.7 ± 1.9	(PF)	7.0 ± 4.5	(HP0, HP2, PF)
SP	5.3 ± 2.5	(HP0, HP2, PF)	7.7 ± 1.7	(HP0, HP2, PF)
CC	3.5 ± 2.9	(HP0, HP2, PF)	14 ± 5.1	(HP0, HP2, PF)
PF	22 ± 7.2	(HP5, HP10, HP30, SP, CC)	32 ± 4.4	(HP5, HP10, HP30, SP, CC)

Stretch values are given as mean ± standard deviation. Listed in parentheses are the tissues whose mean value of stretch differs significantly ($P < 0.05$) based on a one-way ANOVA test with Tukey-Kramer correction for multiple comparisons. Tissues tested include untreated human pericardium (HP0), human pericardium treated for 2, 5, 10, and 30 minutes (HP2, HP5, HP10, and HP30), Supple Periguard (SP), CardioCel (CC), and PhotoFix (PF).

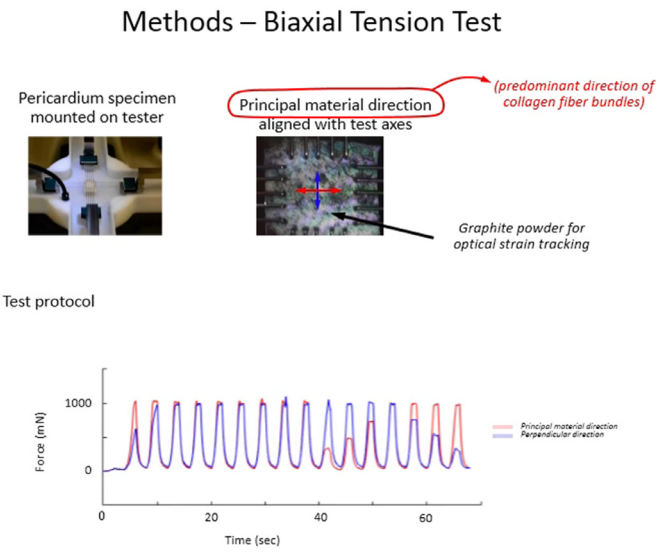
However, the quantitative results that these property changes are nearly complete after 10 minutes of fixation is new and important for our surgical practice. Another notable finding is that PF, in addition to exhibiting similar degrees of stretch to untreated AP, has lower slopes of its stress-strain curves at typical working loads, indicating that at further load increases, the tissue continues to stretch (and consequently thins out) more rapidly than the other tissues tested. Finally, our data indicate the importance of identifying the principal material directions of repair materials, particularly those with pronounced anisotropy like briefly fixed AP, CC, and PF. It would be helpful for commercial pericardium sources to identify the principal material direction so that the surgeon can optimize the patch material orientation for valve repair or vessel augmentation.

Our reported stretch values can be directly applied surgically. For example, we have described a method for design of aortic valve replacement leaflets where leaflet dimensions are based directly on the estimated stretch of the free edge at typical loads, along with the diameter of the sinotubular junction in diastole, and the desired drop angle of the free edge at the commissures.[3] We can also use the stretch data when reconstructing the aortic valve using the method of Ozaki.[4] The leaflet sizers and templates are based on use of autologous pericardium fixed for 10 minutes, but if shorter fixation time (or PF) is used, the leaflet shapes must be scaled down using our stretch data in order to achieve the target closed valve shape. Furthermore, the stretch data are useful for patching vessels like the pulmonary artery, which stretches more in the radial than the axial direction. Optimally orienting the pericardium will better match its compliance with the native vessels.

While this study has limitations — including small sample sizes and neglecting to consider variation in pericardium properties with patient age or harvest site — we think the information will help surgeons achieve more reliable, precision-based valve repair.

SUPPLEMENTARY MATERIAL

The following is the supplementary data to this article:



Video 1. In this video, we briefly state the motivation for the study, describe the mechanical testing method, and summarize the test results for pericardium. An example illustrates how to account for these differences in properties when designing leaflets or patches.

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