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Material modeling of cardiac valve tissue: Experiments, constitutive analysis and numerical investigation

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ABSTRACT

A key element of the cardiac cycle of the human heart is the opening and closing of the four valves. However, the material properties of the leaflet tissues, which fundamentally contribute to determine the mechanical response of the valves, are still an open field of research. The main contribution of the present study is to provide a complete experimental data set for porcine heart valve samples spanning all valve and leaflet types under tensile loading. The tests show a fair degree of reproducibility and are clearly indicative of a number of fundamental tissue properties, including a progressively stiffening response with increasing elongation. We then propose a simple anisotropic constitutive model, which is fitted to the experimental data set, showing a reasonable interspecimen variability. Furthermore, we present a dynamic finite element analysis of the aortic valve to show the direct usability of the obtained material parameters in computational simulations.

1. Introduction

The mechanical modeling of cardiac valve tissues has a long-standing history during which increasingly refined experimental setups and constitutive models have been developed. Early on, experimental testing revealed the highly nonlinear and anisotropic nature of cardiac valve tissues. In Clark (1973), aortic as well as mitral valve leaflets were examined under uniaxial tensile loading, showing a more compliant tissue behavior in the radial direction (perpendicular to the annulus). In Thubrikar et al. (1980), this finding was later confirmed using in vivo tests (via radiopaque markers) and in vitro measurements (by recourse to tensile testing after euthanization). In order to investigate the effects of chemical treatment for bioprosthetic heart valve replacements, biaxial mechanical tests on native and glutaraldehyde-treated porcine aortic valve cusps were performed (Billiar and Sacks, 2000b). Thereby, chemical treatment was shown to significantly lower tissue extensibility. Taking the layered structure of aortic valve tissue into account, strip biaxial tests on the separated ventricularis- and fibrosa layers were performed in Stella and Sacks (2007a), showing that both layers are characterized by a different anisotropic and nonlinear response, whereby the fibrosa layer dominates the mechanical response of the leaflet tissue. With regard to the time dependence in material behavior, the aortic valve's stress–strain response was found to be independent of strain rate (Stella and Sacks, 2007b), thereby confirming earlier studies, in which it was shown that after performing a sufficient number of preconditioning cycles, cardiac valve tissues do not exhibit viscoelastic effects on time scales comparable to the cardiac cycle (Fung, 1993). As a key characteristic typical to biological tissues, heart valve tissues were furthermore shown to not release their aqueous components under compressive loading and are therefore classified as incompressible (Hvidberg, 1960).

Ensuing from experimental investigations, a number of constitutive models based on general considerations of finite elasticity and anisotropy have been proposed in the literature. Thereby, prominant candidates consider contributions from an isotropic elastic matrix in combination with anisotropic exponential fiber terms (Billiar and Sacks, 2000a; Chen et al., 2004; Driessen et al., 2005; May-Newman and Yin, 1998; Prot et al., 2007, 2009; Soares et al., 2014) (some models furthermore consider inhomogeneities based on random fiber angles Billiar and Sacks, 2000a). In a recent investigation, the material parameters of such models were fitted from in vivo displacement measurements and finite element inverse analysis for mitral valve tissue (Rausch et al., 2013; Rausch and Kuhl, 2013). However, most previous studies are limited to

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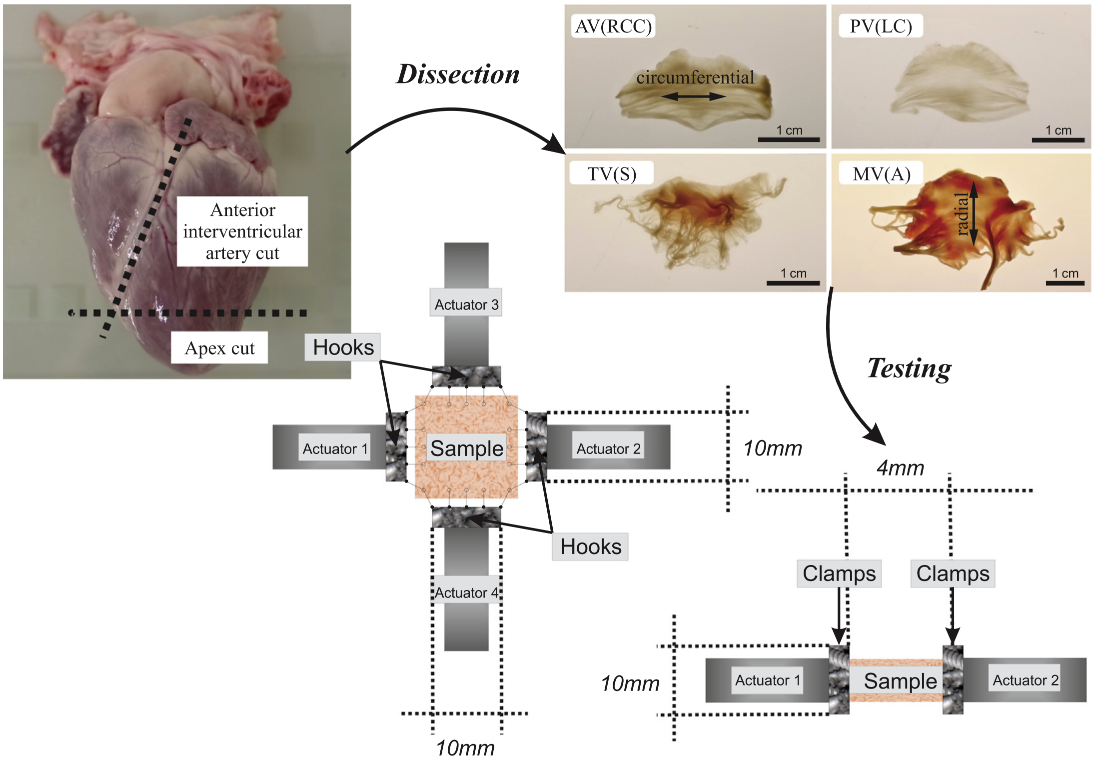

Fig. 1. Dissection of the porcine heart showing main cuts and sample leaflet types of the mitral (MV), tricuspid (TV), aortic (AV), and pulmonary valve (PV), depicted with the corresponding anatomical alignment (radial/circumferential). Harvested samples are used in the illustrated experimental setups (for purposes of detail representation, illustrations are not proportional and length measurements are added).

one particular valve type (see, e.g., Billiar and Sacks (2000b), Christie and Barratt-Boyes (1995), Lo and Vesely (1995), Stella and Sacks (2007a), Stella and Sacks (2007b)), and few studies to two valve types (see, e.g., Clark (1973), Soares et al. (2014)).

To the best of the authors knowledge, there are no works reported in the literature testing all different valve and leaflet types for several individuals under identical experimental conditions. Hence, the present contribution intends to broaden the understanding of the mechanical behavior of cardiac valve tissues by simultaneously:

(i) Performing tensile tests on porcine heart valve leaflets spanning all different valve and leaflet types under identical experimental conditions (Section 2.1) as our key contribution.
(ii) Proposing a simple and micromechanically sound constitutive model (including fiber angles) (Section 2.2).
(iii) Estimating the material constants of the proposed model for all tensile tests (Section 3.1).
(iv) Performing three-dimensional, dynamic finite element simulations of an aortic valve in order to validate that the obtained material constants lead to a physiological valve behavior (Section 3.2).

2. Materials and methods

2.1. Tissue samples and tensile experiments

A total of 87 leaflet samples was tested, spanning all four cardiac valves: the mitral valve (MV) comprising anterior (A) and posterior (P) leaflets; the aortic valve (AV) composed of the left and right coronary (LCC, RCC) and posterior (PC) cusps; the tricuspid valve (TV) consisting of the anterior (A), septal (S), and posterior (P) leaflets; and the pulmonary valve (PV) comprising the anterior (AC), the left (LC), and the right (RC) cusps.

In all cases, dissection of the porcine hearts occurred within a time frame of 3–7 h post mortem, during which the hearts were stored in water at a temperature of 4 °C. During the dissection process, three main cuts allowed for the opening of ventricles and atria, while leaving all valve leaflets intact. The first two cuts were placed along the anterior and posterior interventricular artery, and a final cut was placed right above the apex of the heart (see Fig. 1). Between dissection and testing, the heart leaflets were stored in culture dishes under the same storage conditions as the porcine hearts, with water exchanged every 24 h (within the given time frame during which samples are tested, which lies between 0 and 3 days, prior investigations on porcine aorta tissue performed in our group did not show differences in mechanical behavior between samples stored in physiological solution and samples stored in water). A summary of the different valve leaflets tested is given in Table 1. The larger sample sizes of mitral and tricuspid valve leaflets allowed for testing in the biaxial experimental setup, whereas the aortic and pulmonary valve leaflets were tested uniaxially in the circumferential direction parallel to the annulus, see Fig. 1.

Table 1
Number of harvested samples and ranges of estimated parameter values.

Valve	Harvested samples	Protocol	C (MPa)	G (MPa)	a (−)
AV	18	Uniaxial	0.1–0.95	10–212	2.5–3.6
PV	19	Uniaxial	0.2–0.59	8–157	2.5–3.6
MV	12	Uniaxial	0.1–0.13	5–45	2.5–3.6
MV	8	Biaxial	0.03–0.09	23–102	3.2–4.1
TV	21	Uniaxial	0.1–0.19	7–114	2.8–3.9
TV	14	Biaxial	0.04–0.09	7–114	2.8–4.0

For the experimental testing procedure, rectangular samples were cut from all leaflets. Subsequently, sample thicknesses were measured using a pressure sensitive gauge (Mitutoyo PK – 1012E). Measured mean thicknesses (± standard deviation) for each leaflet type were obtained as: 0.63 ± 0.23 mm (TV-S), 0.69 ± 0.45 mm (TV-A), 0.55 ± 0.28 mm (TV-P), 0.66 ± 0.14 mm (MV-A), 0.87 ± 0.19 mm (MV-P), 0.48 ± 0.11 mm (AV-RCC), 0.51 ± 0.11 mm (AV-LCC), 0.52 ± 0.13 mm (AV-PC), 0.33 ± 0.09 mm (PV-RC), 0.32 ± 0.04 mm (PV-AC), and 0.31 ± 0.11 mm (PV-LC). In the uniaxial cases, samples were fixed using plastic clamps (which were positioned 4 mm apart from each other, see Fig. 1) with a torque wrench that applied a constant force of 0.7 N perpendicular to the tensile plane.

By way of example, an outline of the testing procedure for the uniaxial test case is described below. The samples were first preconditioned by holding them fixed at one end and uniaxially loading them at the other end by moving the actuator following a displacement-controlled procedure up to a maximum displacement corresponding to an applied force of 2 N, see example in Fig. 2. Afterwards, the