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In vitro technique in estimation of passive mechanical properties of bovine heart
Part I. Experimental techniques and data

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Abstract

Myocardium generally demonstrates viscoelastic behavior. Since the stress–stain relationships of tissues are pseudo-elastic, their mechanical behavior can be defined as hyperelastic. In this work, mechanical properties of bovine heart were studied. In this study, the experimental technique for testing myocardium is explained and the experimental data are presented. First, the heart was perfused and the specimens were cut from different regions of the heart. Second, the materials preferred direction was identified. Then, a series of uniaxial, biaxial and equibiaxial test were performed on specimens taken from: left ventricle free wall (LVFW), right ventricle free wall (RVFW), left ventricle mid-wall (LVMW) and apex. Test specimens were preconditioned by applying cyclic load to reduce the viscoelastic effect. After preconditioning, the samples were tested at various stretch rates and loading conditions. Finally, a conclusion is made on the experimental data.

Keywords: Soft tissue; Myocardium; Non-linear elasticity; Anisotropic; Myocardium constitutive relation

1. Introduction

Originally, the mechanical properties of myocardium were approximated by conducting uniaxial tests on papillary tissue or from pressure volume experiments. However, uniaxial or pressure volume tests do not provide sufficient information to predict the multiaxial properties of myocardium [1,2]. Humphrey et al. [3] performed biaxial experiments on five specimens taken from canine left ventricle free wall. They concluded that myocardium is transversely isotropic with the fibre direction being stiffer than the cross-fibre direction. Humphrey and Yin [4] more rigorously determined the constitutive relation for excised non-contracting myocardium based on the assumption of incompressibility and transverse isotropy. Recently, the systolic function of the heart has been studied [5–7]. In these works, the inter-laminar shear strain and its relation to laminar structure had been thoroughly investigated. Thus, the physiology and the dynamic response of myocardium in systolic phase have been the main focus.

There are very limited numbers of biaxial tissue experiments reported to date [1,8–10]. Most of the experimental results are presented in the form of strain energy functions. These strain energy functions are mostly defined either as an exponential or polynomial function of the strain invariants. Generally, the constitutive equations are derived from strain energy functions and experimental data are fitted to the stress–strain equation using non-linear curve fitting techniques. This technique results in a wide variability in material parameters [2–4,8,10–12]. It is assumed that the intra-specimen variability is either the artefact of strain energy function or the strain history dependence of myocardium. Yin et al. [12] conducted various biaxial experiments and proposed a strain energy function that reduced the variability of the material parameters. However, in their study, they only used the data from equibiaxial experiments. Various uniaxial and biaxial experiments have been reported on LVMW and

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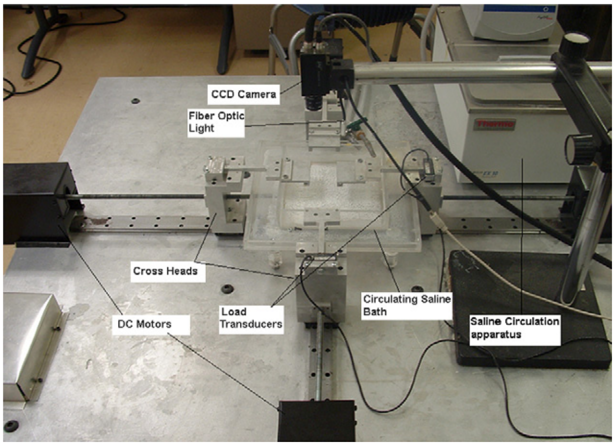

Fig. 1. Biaxial testing apparatus.

LVFW [13,2]. However, very limited work has been reported on the right ventricle's free wall (RVFW) [14–16], and no work has been reported on tissues taken from apex.

Recently, medical imaging primarily by MR has allowed analysis of wall motion under *in vivo* condition. Consequently, number of theoretical approaches has been proposed to study the cardiac dynamic function and to calculate the stresses theoretically [17,18]. Moreover, valuable works have been conducted on determining the mechanical response of tissue such as aortic and mitral valve [19,20]. These works provided valuable information on structure and fiber distribution, local mechanical properties and constitutive modeling of beating heart. Recent works have been focused on active and beating function of LV myocardium and have not addressed the need for a comprehensive experimental data of passive myocardium mechanical properties. Consequently, more experimental data are required to accurately study the passive response of myocardium and this work aims to address this issue. The outline of this study is as follows: the apparatus and experimental method are first explained, then the material and sample preparation is explained, next the experimental data are presented and finally a conclusion is made on the physical response of soft tissue to the mechanical loading.

2. Experimental method

2.1. Testing apparatus

In this study, a biaxial, electromechanical tensile testing machine was designed. The tensile testing machine employs two DC servomotors with optical encoders, one for each axis. A data acquisition system was used for data collection and control. Four T-shaped grips were designed so that test specimen of up to 5 cm × 5 cm × 0.15 cm could be gripped for testing. The ends of the grips were attached to a load transducer of maximum 10.00 N with ±0.1% resolution. The control algorithm of the tensile testing machine was developed such that the main means of controlling was displacement (load control test can be performed). The displacement test tends to reduce the possibility of inhomogeneous deformation as the displacement in each axis is closely controlled. Fig. 1 depicts the apparatus. To keep the tissue in physiological state, a heating bath and saline solution circulating apparatus was added to the system. Further, to ensure that a pH of 7.4 is maintained in the solution, the solution was buffered by 95% O_2 and 5% CO_2. The pH of the solution was measured using a hand held pH indicator.

It is well known that the deformation is non-homogeneous near the grip due to grip effects. It was assumed that the fiber direction through the thickness was constant and deformation at the center of the specimen was homogeneous. Thus, it was essential to measure the deformation at the center of the test specimen. A CCD camera and capture card was adapted to the system to measure the displacement at the center of the specimen. The data acquisition algorithm was developed to simultaneously record the displacement of the cross-head, load from the transducers and the images taken by the CCD camera at a controllable rate.

The strain at the center of the specimen was measured by drawing a 5 mm × 5 mm square section on the center of the specimen using enamel ink. A reference image was taken from the sample at rest. Then the consequent digital images were used throughout the test. The determination of stretch ratios was made after the test protocols were

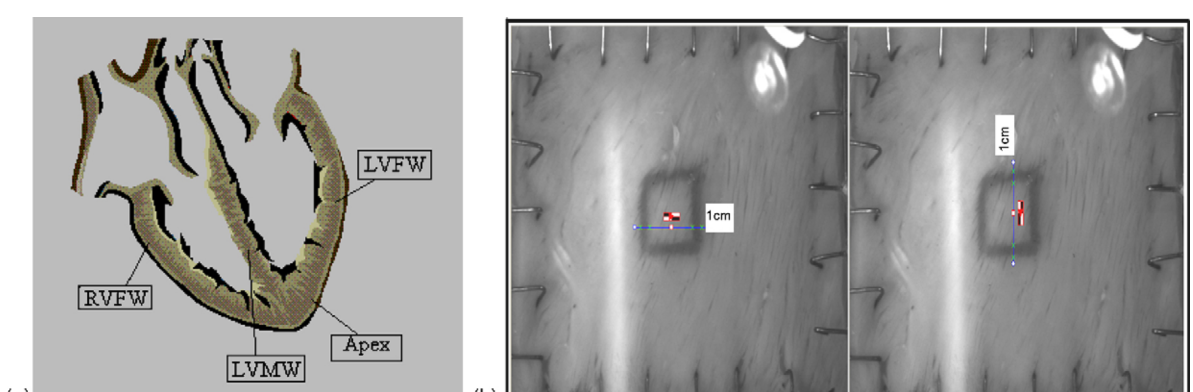

Fig. 2. (a) Specimens locations and (b) the specimen in the grip. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)