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Journal of the Mechanical Behavior of Biomedical Materials

Research Paper

Biomechanical behavior of bovine periodontal ligament: Experimental tests and constitutive model

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ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form 17 May 2016
Accepted 30 May 2016
Available online 4 June 2016

Keywords:
Periodontal ligament
Experimental test
Nonlinear viscoelasticity

ABSTRACT

A viscohyperelastic constitutive model with the use of the internal variables approach was formulated to evaluate the nonlinear elastic and time dependent anisotropic mechanical behavior of the periodontal ligament (PDL). Since the relaxation response was found to depend on the applied stretch, the adoption of the nonlinear viscous behavior in the present model was necessary. In this paper, Helmholtz free energy function was assigned to the material as the sum of hyperelastic and viscous terms which is based on the physical concept of internal variables. The constitutive model parameters were evaluated from the comparison of the proposed model and experimental data. For this purpose, tensile response of the bovine PDL samples under different stretch rates was obtained. The good correspondence between the proposed model and the experimental results confirmed the capability of the model to interpret the stretch rate behavior of the PDL. Moreover, the validity of structural model parameters was checked according to the results of the stress relaxation tests.

1. Introduction

The periodontal ligament (PDL) is the connective tissue which links the tooth to the surrounding bone (Berkovitz et al., 1995). In addition to the tooth support, the PDL plays an important role in distribution of occlusal forces on the alveolar bone and prevents stress concentration during mastication (Shuttleworth and Smalley, 1983; Yoshida et al., 2001). The PDL is also responsible for bone remodeling during orthodontic tooth movement (Picton, 1989). Mentioned mechanical functions can be attributed mainly to the following structural elements of the PDL: (1) the collagen and elastic fibers, (2) the ground substance which consists of 30% glycoproteins and proteoglycans, and 70% bound water, and (3) the vasculature (Berkovitz et al., 1995; Shuttleworth and Smalley, 1983). Understanding functions of the PDL is necessary to characterize its mechanical behavior (Natali et al., 2004; Picton, 1989).

In vitro mechanical tests of the PDL have been carried out by various authors. For example, Dorow et al. (2003) and Pini et al. (2004) using uniaxial tensile tests found that the PDL exhibits the nonlinear elastic (hyperelastic) response. Komatsu et al. (2007), Natali et al. (2004), Sanctuary et al.

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http://dx.doi.org/10.1016/j.jmbbm.2016.05.036
1751-6161/

(2005) and Shibata et al. (2006) found time dependent (viscous) properties of the pig and bovine PDL samples with stress relaxation tests. They found that the relaxation rate depends on the applied stretch, i.e. a nonlinear viscous behavior. Also, Komatsu and Chiba (1993) and Sanctuary et al. (2005) found a stretch rate dependent mechanical behavior of the PDL.

Based on the mentioned experimental studies, it could be concluded that the PDL represents a nonlinear viscoelastic behavior. The nonlinear elastic response of the PDL in tension can be attributed to crimped configuration of fibers (Natali et al., 2011), whereas rearrangement of fibrous structures in tension and fluid fluxes in compression can lead to viscoelastic effects (Natali et al., 2004).

Constitutive modeling of the soft biological tissue is a useful tool as a rational interpretation of its mechanical properties and prediction of their mechanical response under various loading states (Natali et al., 2015). Definition of an accurate constitutive model, considering structural configuration and experimental results, represents a reliable and promising approach to study the biomechanics of the tissues (Kroon and Holzapfel, 2008; Maurel et al., 1998; Natali et al., 2010).

Different constitutive models of the PDL reported in literature can be classified as linear elastic (Panagiotopoulou et al., 2011), hyperelastic (Aversa et al., 2009), viscoelastic (Natali et al., 2004; Natali et al., 2011), or biphasic poroelastic (Bergomi et al., 2011). Although multi-phase models are suitable to describe the microscopic behavior of the soft tissues, viscoelastic modeling is an appropriate technique for describing the overall tensile response of the PDL (Natali et al., 2004). Thus, a full characterization of the tensile mechanical response of the PDL demands formulation of an appropriate constitutive model capable to demonstrate its nonlinear viscoelastic behavior. The majority of viscoelastic constitutive models of the PDL, like other biological tissues, were proposed based on Fung's (1993) quasi-linear viscoelastic (QLV) formulation (Toms et al., 2002). Although this formulation is one of the most well-known constitutive models in the field of the biomechanics, nevertheless, has an important drawback: it is unable to describe the nonlinear viscous phenomena (Provenzano et al., 2002; Troyer and Puttlitz, 2012). Other papers, like Zhurov et al. (2007) proposed a transversely isotropic viscohyperelastic constitutive model with 17 invariants by defining a viscous energy function which involved time derivative of the right Cauchy–Green deformation tensor. This approach seems to be appropriate for modeling of viscoelastic behavior of the tissues with a strong dependency on the stretch rates; however it is valid only for a specific range of rates.

A more recent approach of viscoelastic modeling for biological tissues is based on the physical concept of internal variables. This approach assigns a Helmholtz free energy function to the materials as the sum of hyperelastic and viscous terms, where the latter term represents the total energy dissipated in the tissues (Holzapfel et al., 2000; Natali et al., 2011; Peña et al., 2007). The constitutive model with internal variables is amenable to a rather straightforward and efficient numerical implementation (Peña et al., 2008). In addition, the model is capable of accounting for distinct viscoelastic behaviors of the ground substance and fibers (Holzapfel et al., 2000; Peña et al., 2007).

The objective of this paper was to present a comprehensive viscoelastic model for the simulation of the response of PDL. The proposed constitutive model was formulated to evaluate the nonlinear elastic and time dependent anisotropic mechanical behavior of the PDL. The adoption of the nonlinear viscous behavior in the present model was considered similar to formulation proposed for other soft tissues, such as knee ligaments (Peña et al., 2008) to predict relaxation rate dependence on the applied stretch. In this work, Helmholtz free energy function was assigned to the material as the sum of hyperelastic and viscous terms which is based on the physical concept of internal variables. The constitutive model parameters were evaluated from the comparison of the proposed model and experimental data. For this purpose, tensile response of the bovine PDL samples along fiber direction under different stretch rates was obtained.

2. Materials and methods

2.1. Sample preparation

Sample preparation consisting of dentin, PDL and bone were done according to a technique previously described (Oskui and Hashemi, 2016). In brief, a fresh bovine mandible was obtained and separated into right and left first molar dental blocks with the surrounding PDL and bone. The blocks were sectioned into slices perpendicular to the longitudinal axis of the molar tooth and samples extracted with $2\times4\times8$ mm dimensions from slices (Fig. 1). These samples were cut so that the collagen fibers of the PDL were approximately aligned in mechanical testing direction. A total of 24 samples were selected for the mechanical tests. Before tests, the initial length of PDL for each sample (l_0) was measured with an optical microscope.

2.2. Test procedure

The displacement-controlled mechanical tests were carried out using a material testing machine. The displacement was monitored via a linear variable differential transformer with 1μm accuracy and load was measured with a 500 N load cell. The bone and dentin segment of samples were attached to

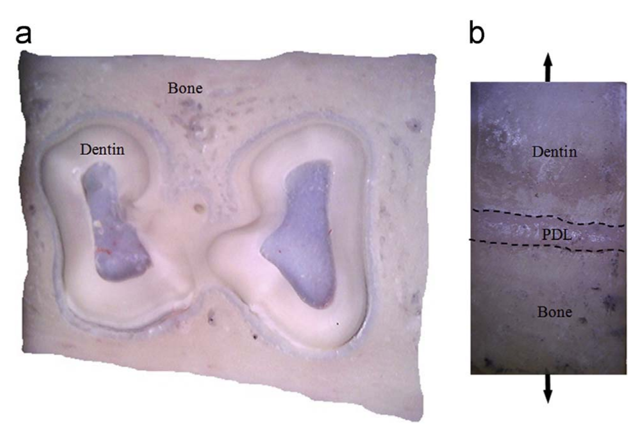

Fig. 1 – (a) Photograph of typical transverse section of the molar tooth; and (b) Sample used for tensile test composed of bone, the PDL and dentin.