Archives of Oral Biology 76 (2017) 20–29

Contents lists available at ScienceDirect

Archives of Oral Biology

journal homepage: www.elsevier.com/locate/aob

Time dependent deformation behavior of dentin

C. Montoya[a], D. Arola[b,c], E.A. Ossa[a,*]

[a] School of Engineering, Universidad Eafit, Medellín, Colombia
[b] Department of Materials Science & Engineering, University of Washington, Seattle, WA, USA
[c] Departments of Restorative Dentistry and Oral Health Sciences, School of Dentistry, University of Washington, Seattle, WA, USA

ARTICLE INFO

Article history:
Received 21 September 2016
Received in revised form 15 November 2016
Accepted 3 January 2017

Keywords:
Dentin
Spherical indentation
Creep
Mineral-to-collagen ratio
Lumen area fraction

ABSTRACT

Objective: The viscoelastic behavior of dentin and its ability to undergo time dependent deformation are considered to be important to oral functions and its capacity to resist fracture. There are spatial variations in the microstructure of dentin within the crown, which could be important to the viscous behavior. However, a spatially resolved description for the viscoelastic behavior of coronal dentin has not been reported.
Methods: In this investigation spherical indentations were made in three regions of coronal dentin including the outer, middle and inner regions. Power law relations were developed to quantitatively describe the stress-strain responses of the tissue.
Results: Results showed that the deformation behavior was strongly dependent on the composition (mineral to collagen ratio) and microstructure (tubule density), which contributed to an increase in the rate of viscous deformation with increasing proximity to the pulp.
Conclusions: A model accounting for spatial variations in composition and microstructure was developed to describe the steady-state time dependent deformation behavior of coronal dentin, and a good agreement was found with the experimental results.

1. Introduction

Most biological tissues exhibit viscoelastic behavior, which is considered to be important to their function. For instance, the time dependent deformation behavior of dentin potentially contributes to the distribution of loads within the tooth and the resistance to fracture (Duncanson & Korostoff, 1975; Kinney, Marshall, & Marshall, 2003; Trengrove, Carter, & Hood, 1995).

The mechanical response of dentin results from the interaction between the organic and mineral constituents. Dentin consists of approximately 45% mineral, 33% organic material (collagen type I) and 22% water by volume (Nanci, 2008). Although this chemical composition is assumed for the tissue overall, it has been widely recognized that these percentages change spatially within the tooth (Montoya, Arango-Santander, Peláez-Vargas, Arola, & Ossa, 2015; Ryou et al., 2011; Tesch et al., 2001; Xu, Yao, Walker, & Wang, 2009). The combination of hard mineral crystals (i.e. hydroxyapatite) and highly viscous organic material (i.e. collagen) results in a viscoelastic material with time dependent behavior (Deymier-Black et al., 2012; Kinney et al., 2003; Shen, Kahn, Ballarini, & Eppell, 2011). Microscopic evaluations of the microstructure are dominated by the dentinal tubules, which are a network of small (diameter of approx. 1 μm) canals that traverse the entire thickness of dentin. The tubule density ranges from 20,000 to 55,000 tubules/mm^2 and may function hydraulically during stress transfer (Nanci, 2008; Pashley, Okabe, & Parham, 1985).

The mechanical properties of dentin have been extensively investigated in response to quasi-static tension, bending and shear loading. A comprehensive review of these studies was reported by Kinney et al. (2003). Few studies have analyzed the time dependent behavior of dentin. For instance, Korostoff, Pollack, & Duncanson (1975) analyzed the viscoelastic behavior of radicular dentin under compressive loads, finding that the relaxation modulus exhibited a linear dependence on the logarithm of time. The mathematical model of viscoelasticity previously presented by Alfrey and Doty (1945) was compared with their experimental results and suggested that the stress relaxation response of dentin follows a linear viscoelastic behavior. However, due to the differences in microstructure between the crown and root (Arola et al., 2009), it is not clear if this behavior can be extrapolated to coronal dentin. On the other hand, Jafarzadeh, Erfan, and Watts (2004) evaluated coronal dentin under two different compressive stresses and temperatures and reported linear viscoelastic behavior. Nevertheless, the spatial variations in microstructure

* Corresponding author at: School of Engineering, Universidad Eafit, Cra 49 No 7 sur 50, Medellín, Colombia.
E-mail address: eossa@eafit.edu.co (E.A. Ossa).

http://dx.doi.org/10.1016/j.archoralbio.2017.01.003
0003-9969/

and tubules were not considered, which could contribute to the time dependent behavior of this tissue.

Using nano-Dynamic Mechanical Analysis (DMA), Ryou, Romberg, Pashley, Tay, and Arola (2012) studied the viscoelastic behavior of peritubular and intertubular dentin separately. Indentations were made with a dynamic load amplitude of 20 μN, and over frequencies varying from 2 to 100 Hz. The dynamic mechanical properties increased in magnitude with loading frequency. Interestingly, although the complex and storage moduli of peritubular dentin were significantly larger than those for intertubular dentin, there were no significant differences in the loss modulus and *tanδ* between the intertubular and peritubular dentin. Recently, Chuang et al. (2015) performed nanoindentation creep tests to study the viscoelastic properties of dentin after de- and re-mineralization processes. Demineralization increased the primary and secondary creep regimes, whereas remineralization reduced the primary creep response of dentin without changes to the viscoelastic behavior. Additional creep tests on dentin have also been reported (Han et al., 2012; Bertassoni, Kury, Rathsam, Little, & Swain, 2015).

Indentation techniques have been widely used to analyze the viscoelastic properties of tissues and biological materials (i.e. bone and teeth) (Staines, Robinson, & Hood, 1981; Ahearne, Yang, Then, & Liu, 2007; Cheneler, Mehrban, & Bowen, 2013). Indentation is an attractive method due to its ability to obtain reliable results without causing substantial damage to the tissue. Of course, there is permanent deformation to the sample, which is a function of indenter shape and load. Various types of indenters have been used for these tests such as spherical, conical and pyramidal. Sharp indenters introduce a discontinuity at the tip followed by immediate inelasticity, while spherical indenters produce a uniform and axisymmetric distribution of stresses, allowing a soft transition between elastic and viscoelastic regimes during the indenter penetration, simplifying the viscoelastic behavior analysis of the material (Bower, Fleck, Needleman, & Ogbonna, 1993; Kim, 2008).

Despite these previous studies for the viscoelastic properties of dentin, little is known about its time-dependent deformation and the effect of spatial variations within the crown. During mastication coronal dentin is subjected to a variety of cyclic stresses in which the viscoelastic response of the tissue could deter crack initiation, and increase the resistance to fracture. Understanding the time-dependent loading deformation behavior of coronal dentin and the contribution of spatial variations in microstructure is important to understand the structural behavior of teeth and in the development of new dental materials with mechanical properties consistent with those of the hard tissue. Therefore, the aim of this work was to develop a simple model for the time dependent loading deformation behavior of coronal dentin in the steady-state regime (or secondary creep), considering the spatial variations in microstructure and composition within dentin. First, an experimental study of the spherical indentation behavior of coronal dentin is presented. Based on the experimental results, a model based on previously proposed theories for indentation of time dependent materials is proposed and validated.

2. Background

Several models have been proposed to determine the displacement and stress fields produced in a time dependent material under a rigid indenter (e.g. Bower et al., 1993; Graham, 1965; Hunter, 1960; Lee and Radok, 1960). Bower et al. (1993) solved the problem of axisymmetric indentation of a half-space comprised of a power-law creep material of the form:

$$\dot{\varepsilon} = \dot{\varepsilon}_o \left(\frac{\sigma}{\sigma_o}\right)^n, \quad (1)$$

using the similarity transformations suggested by Hill, Storakers, and Zdunek (1989), where σ_o and $\dot{\varepsilon}_o$ are the reference stress and strain rates, and n the power law creep exponent of the material. These transformations are based on the observation that at any given instant, the velocity, strain rate and stress fields in the half-space only depend on the size of the contact a and the indentation rate $\dot{h}$, and are independent of the loading history (see Fig. 1). Thus, the general indentation problem is reduced to calculating stresses and displacements in a non-linear elastic solid, indented to a unit depth by a rigid flat punch of unit radius (in the axisymmetric problem). For indentation by a frictionless spherical indenter, the similarity solutions dictate that the contact radius a is related to the indentation depth h by:

$$a = c\sqrt{2Rh}, \quad (2)$$

where a is the contact radius and R is the radius of the indenter. The constant c is only a function of the material creep exponent n and may be thought of as the ratio of the true to nominal contact radius, where the nominal contact radius is $\sqrt{2Rh}$. Similarly, the applied load F is related to the indentation rate $\dot{h}$ via:

$$\frac{F}{\pi a^2 \sigma_o} = \alpha\left(\frac{\dot{h}}{a\dot{\varepsilon}_o}\right)^{1/n} = \alpha\left(\frac{\dot{a}}{\dot{\varepsilon}c^2 R}\right)^{1/n}, \quad (3)$$

where the constant α is again only a function of the power-law exponent n. Values of c and α for selected values of n were deduced by Bower et al. (1993) from a series of finite element calculations and are listed in Table 1. Eqs. (2) and (3) can be written in terms of an effective stress and effective strain under the indenter. The effective stress σ^{eff} under the indenter is defined as

$$\sigma^{eff} = \frac{F}{\pi a^2}, \quad (4)$$

while the effective strain and strain rate under the indenter are specified as

$$\varepsilon^{eff} = c\sqrt{\frac{h}{2R}}, \quad (5)$$

and

$$\dot{\varepsilon}^{eff} = \frac{\dot{a}}{2R} = c\frac{\dot{h}}{2\sqrt{2hR}}, \quad (6)$$

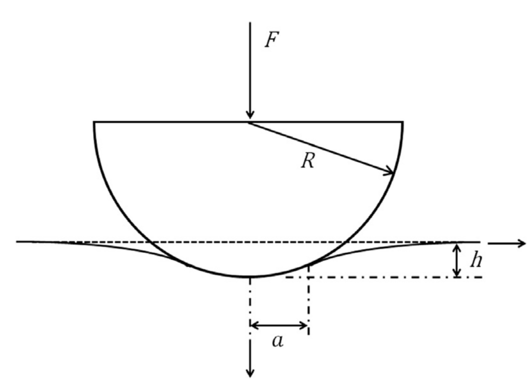

Fig. 1. Schematic diagram of a half-space under indentation by a rigid sphere. The variables F, R, h and a represent the indentation force, indenter radius of curvature, depth of indentation and the radius of permanent indentation, respectively.