The Veterinary Journal 198 (2013) 583–589

Contents lists available at ScienceDirect

The Veterinary Journal

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

Finite element analysis of equine incisor teeth. Part 1: Determination of the material parameters of the periodontal ligament

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ARTICLE INFO

Article history:

Keywords:
Equine dentistry
Finite element analysis
Horse
Incisors
Peridontium

ABSTRACT

In equine dentistry, periodontal diseases are frequently found in aged horses. Excessive strains and stresses within the periodontal ligament (PDL) occurring during the masticatory cycle may be predisposing factors especially in old horses with short, worn teeth. The finite element (FE) analysis is a valuable tool to investigate such strains and stresses in biological materials but a precondition for a realistic and reliable FE analysis is accurate knowledge of material parameters. As no data exist concerning the PDL of equine incisor teeth, this study was undertaken to determine the equine specific, age related and load dependent Young's modulus of equine incisors.

To determine the biomechanical behaviour of the PDL, the incisor jaw-regions of horses of different ages were sectioned into 5 mm thick slice samples and the incisors experimentally intruded (i.e. axially displaced into the alveolus) while recording the load–displacement relationship. Based on high resolution micro-computer tomography (μCT)-datasets, reliable and detailed 3-dimensional models of the slice samples were constructed focusing on precisely modelling the anatomy of the PDL. FE calculations were then performed and set-actual comparisons of the FE results with the experimentally measured displacements enabled the Young's modulus of the PDL to be determined.

The results of this study reflect the typical non-linear behaviour of the collagen fibres of the PDL and present a high load dependency of the PDL's Young's modulus. Further investigations calculating the strains and stresses within the periodontal ligament, teeth and surrounding bone of the entire rostral aspect of the jaw are warranted.

Introduction

Finite element (FE) analysis in human dentistry is a common and highly useful tool for simulating biophysical effects on biological material using computerized models. In recent studies, FE analysis was used to determine material parameters of different periodontal tissues, such as the periodontal ligament (PDL) (Rees and Jacobsen, 1997; Vollmer et al., 2000) and the surrounding bones (Rho et al., 1993). Furthermore, it facilitated the investigation of tooth displacements (Bourauel et al., 1999) and the calculation of strains and stresses occurring within the PDL and its surrounding tissues (McGuinness et al., 1991; Cattaneo et al., 2005; Ona and Wakabayashi, 2006).

The initial FE analyses of equine teeth were carried out by Lüpke et al. (2010), simulating masticatory forces in equine cheek teeth during different phases of the masticatory cycle and investigating biomechanical effects on the PDL, tooth and bone. Cordes et al. (2012b) investigated the PDL's Young's modulus of equine cheek teeth using FE-models of teeth from three different age groups. In a further study, stresses and strain energy densities (SEDs) in the PDL of equine cheek teeth as well as in the surrounding bones were determined (Cordes et al., 2012a).

The PDL of horses is a highly specialized tissue with two main functions: (1) to firmly and flexibly attach the tooth to its alveolus, and (2) to take up masticatory forces with its collagen fibres and blood vessel system (Mitchell et al., 2003; Staszyk and Gasse, 2005). Furthermore, the PDL keeps the tooth in occlusion by compensating the dental wear through prolonged eruption of the tooth (Staszyk et al., 2006). Dental wear in combination with prolonged eruption results in a shortening of the intra alveolar parts of the tooth. Thus, the attachment area of the PDL decreases noticeably with age causing reducing areas to take up the masticatory forces (Staszyk et al., 2006).

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http://dx.doi.org/10.1016/j.tvjl.2013.10.009

Cordes et al. (2012a) hypothesized that stress concentrations in distinct areas of the cheek teeth PDL during mastication might cause local necrosis, providing a suitable environment for microorganisms, and indicating a correlation between the shortening of the intra alveolar parts of the tooth and increased dental problems in old horses. We propose that high local stresses in the equine incisor PDL also occur, initiating high strain accumulations that induce local over-distension of the collagen fibre apparatus. Resulting micro-necrosis might be a predisposing factor for the development of periodontal diseases, such as the equine odontoclastic tooth resorption and hypercementosis (EOTRH).

The aim of the present study was to determine Young's modulus of the equine incisor PDL. No literature exists about this material property and the predictive ability of the FE simulations highly depends both on the quality of the applied material parameters and the level of detail of the 3-dimensional (3-D) models (Wakabayashi et al., 2008). Therefore, intrusive displacement experiments were performed, detailed and realistic 3-D models of the samples were subsequently constructed, and FE calculations were realized. This enabled us to progress to the second step, presented in Part 2 of this study (Schrock et al., 2013), in which we were able to simulate tooth movements, and to predict SEDs in the incisor teeth, the PDL, and the surrounding bones in horses of different ages.

Materials and methods

Preparation of slice samples

The rostral aspects of upper and lower jaws of three horses of different ages (6, 17.5 and 22 years), were obtained and deep frozen. The rostral aspects were bisected in the median plane using a diamond-coated band saw (type MBS 220/E, Proxxon), and subsequently cut into 5 mm thick slices perpendicular to the long axis of the intra alveolar part of the middle (Triadan 02) incisor. Each slice sample contained the tooth of interest (Triadan 02), its PDL, the adjacent teeth, and the surrounding bony structures (cortical alveolus, cancellous, and compact bone). The slice samples for testing were taken from different positions of the clinical root, namely, alveolar-crest level, mid-root level, and root-tip level (Table 1).

The samples were embedded in methylmethacrylate resin (VariDur 3000, Buehler) with the occlusal part of the cut surface showing upwards. The occlusal cut surface of the slice sample, as well as the apical cut surface of the tooth of interest (Triadan 02), were left free of embedding material. To guarantee freedom of tooth mobility in the apical direction, the embedding material of the apical surface (which was to be positioned on the supporting surface of the testing machine) overhung the tooth by about 4 mm. The specimens were placed on icepacks to minimize thermal stress within the PDL during resin hardening (an exothermic process). After hardening, the samples were refrozen and sanded down with sandpaper to ensure smooth surfaces.

Construction of 3-D models

The slice samples were scanned by a µCT-system (XTremeCT, Scanco Medical) with an isotropic spatial resolution of 82 µm. The occlusal cut surface of each slice sample was adjusted parallel to the scan direction. For each specimen 120–180 cross-sectional images were created. The obtained DICOM (Digital Imaging and Communications in Medicine) datasets were imported into the computer program AMIRA (version 5.4.3, Visualization Sciences Group). Using internal program functions, 3-D models were semi-automatically constructed. The tooth (composed out of dentin, enamel, and cementum), as well as the surrounding bone (composed of alveolus, cancellous, and cortical bone) were constructed uniformly assuming it only consisted of one homogeneous, isotropic material (Kawarizadeh et al., 2003). The PDL was constructed manually filling the periodontal space (e.g. the space between tooth and alveolus bone) with homogeneous material.

Surface and tetrahedral volume meshes were then generated for the 3-D models as described by Lüpke et al. (2010) (Fig. 1). To optimize net quality the volume meshes were remeshed and transferred to the computer program COMSOL Multiphysics (version 4.3a, COMSOL AB) for finite element analysis. To ensure adequate net quality, all meshes were tested by a program internal quality measuring function, evaluating the aspect ratios of the tetrahedral elements. COMSOL indicates that mesh topology does not negatively affect FE solutions when mesh quality q is larger than 0.1. For our FE simulations only suitable volume meshes (i.e. only a minimum of tetrahedrons with $q < 0.1$) were used.

Determination of material parameters

For FE analyses, the material parameters for each structure of the 3-D mesh had to be predefined. Properties describing the elastic behaviour of materials are Young's modulus and Poisson's ratio. As the values for Young's moduli and Poisson's ratios for teeth (Kawarizadeh et al., 2003; Cattaneo et al., 2005; Ziegler et al., 2005) and bony structures (Abé et al., 1996; Vollmer et al., 2000) as well as the Poisson's ratio of the PDL (Rees and Jacobsen, 1997; Toms and Eberhardt, 2003) were shown to be uniform in several studies, values for these parameters were obtained from the literature (Table 2).

The published values for Young's moduli of the PDL however vary greatly depending on the investigated species and the measuring methods (Poppe et al., 2002; Dorow et al., 2003; Pini et al., 2004). Cordes et al. (2012b) determined values for the PDL of equine cheek teeth by intrusive displacement experiments in jaw segments of horses of three different age groups. In order to obtain incisor specific data in our study analogue intrusive displacement experiments were conducted. All materials in the models were assumed to be isotropic and linear elastic, although the properties of the PDL were proven to be viscoelastic showing a non-linear behaviour (Picton and Wills, 1978; Pini et al., 2004; Shibata et al., 2006).

Validation

To verify the applicability of our 3-D models FE simulations were performed by varying the PDL's Young's moduli and the applied loads in a wide but realistic range (i.e. Young's moduli from 1 to 11 MPa and loads from 10 to 500 N). It can be expected that our models are applicable in the specified property range when the curve's course representing the load–displacement relationship is linear and the curve's slope increases proportionally to the applied Young's moduli.

In addition, FE calculations were performed with drastically varied material parameters for bone and tooth (i.e. Young's modulus varied by a factor of 0.01 and 100). This enabled us to draw useful conclusions on the influence of these material parameters (not further determined in this study) on our calculated values of the PDL's Young's modulus.

Intrusive displacement experiments

After thawing to room temperature the embedded slice samples were placed in a computer-controlled material testing machine (Type 20 K, UTS Test Systems) (Fig. 2).

The tooth of interest was loaded by a piston in an occluso-apical direction. The piston moved with an increasing axial force and a velocity of 10 µm/s. The amount of intrusion was measured by an electro-optical displacement sensing system with a resolution of 1 µm using the piston socket and the surface of the slice sample as reference for the sensing fork. Repeated force applications were performed by stop-

Table 1
Slice sample number, position of the slice samples, rostral aspect of the jaw (Triadan), and horse age.

Slice number	Position of the slice samples	Rostral aspect (Triadan)[a]	Horse age (years)
03	Alveolar-crest level	200	22
05	Root-tip level	300	22
09	Alveolar-crest level	200	17.5
11	Alveolar-crest level	300	17.5
19	Alveolar-crest level	200	6
22	Mid-root level	200	6
23	Alveolar-crest level	300	6
25	Mid-root level	300	6
26	Mid-root level, apical next to slice number 25	300	6

[a] Modified Triadan nomenclature (Triadan, 1972; Floyd, 1991).